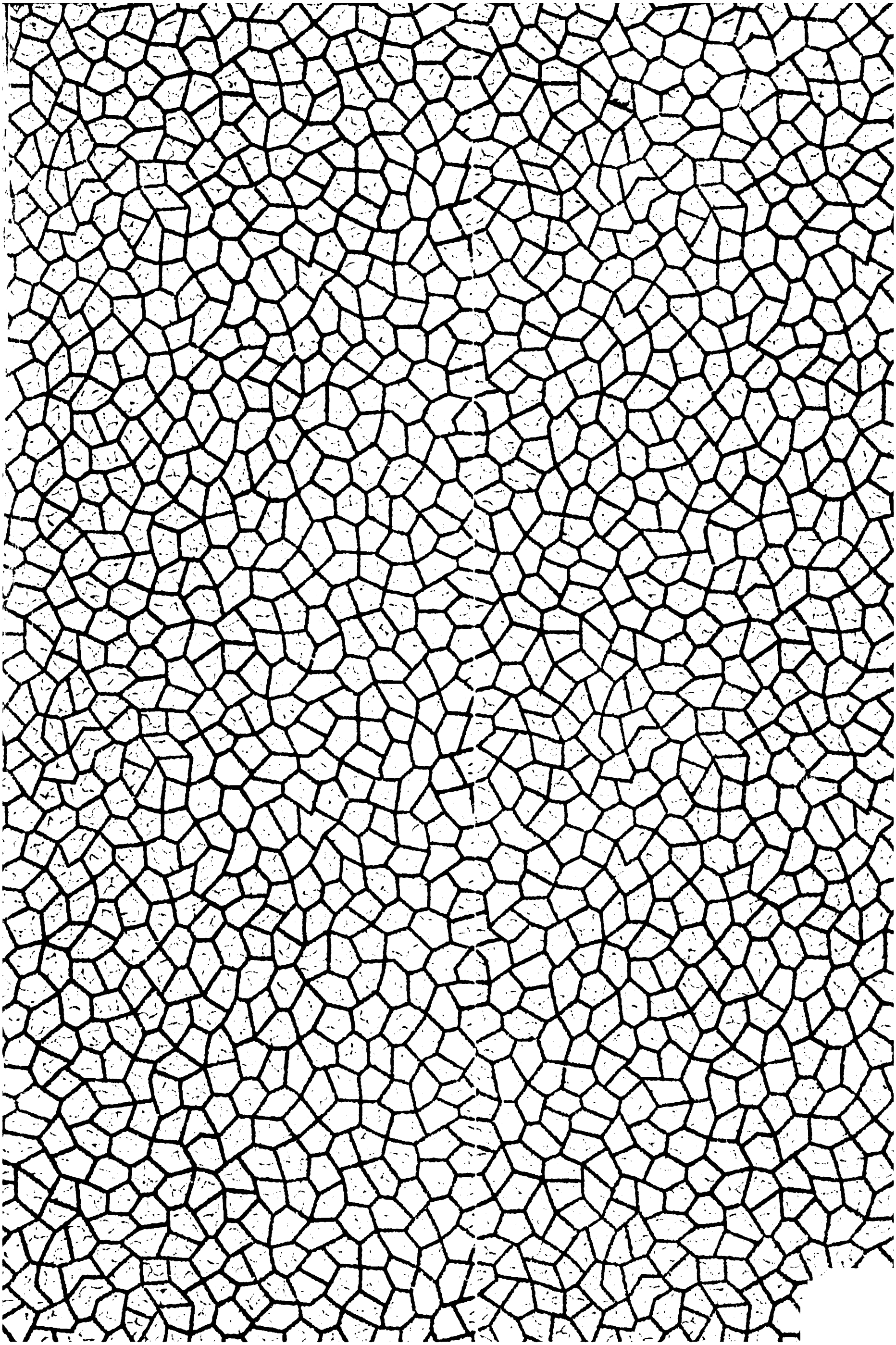

# PRACTICAL WORK IN PHYSICS

## PART IV. MAGNETISM AND ELECTRICITY

*WOOLLCOMBE*

HENRY FROWDE, M.A.

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# *Practical Work in Physics*

*FOR USE IN SCHOOLS AND COLLEGES*

BY

alter eorge
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## PART IV. MAGNETISM AND ELECTRICITY

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'Quo teneam vultus mutantem Protea nodo?'

HOR., *Ep.* I. i. 90.

# PREFACE

AN essential feature in the four parts of *Practical Physics for Schools and Colleges*, of which this is the fourth, is to offer a fairly complete experimental course in the ground covered at a trifling cost. A good deal of the apparatus for this part can be made without much skill, but some of it must be purchased, and the first cost is somewhat greater than is the case in the other branches of Physics. The arrangement of the experiments may be open to criticism, but, in the author's view, it is the best for a book of this class. It need not be systematically followed, and the teacher can use his own judgement as to the order which he adopts. In addition to what was stated in the Introduction to the first part, it may be remarked that it is important before beginning an experiment to adjust the measuring instruments in their proper positions as carefully as possible, and that, in doing the electrical experiments, the student should be sure that the connexions are

correct, and that the current and resistances in circuit are arranged so as to get as accurate a result as possible.

In completing the series the author acknowledges with thanks the reception it has received, and is glad to know that it has been found to supply a real want.

KING EDWARD'S HIGH SCHOOL, BIRMINGHAM,
*November*, 1898.

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# I. MAGNETISM

IN addition to the apparatus and material usually at hand in a Chemical Laboratory, the following will be required. Those in italics are not indispensable.

Two bar magnets.
Thin magnetized rod about 30 cm. in length.
Three bar magnets about 10 cm. in length.
Two bar magnets about 2 cm. in length.
*Uniformly magnetized steel disk.*
*Dip-circle.*
Compass needle (see Note 1).
Magnetoscope (see Note 6).
Magnetic needle supported on a pivot.
*Magnetometer.*
*Vibration box.*
Half-metre rule.

*The apparatus required for this volume may be obtained from* Mr. W. GROVES, 89 *Bolsover Street, Portland Place, W., who will send a price-list on demand.*

# PRACTICAL WORK IN MAGNETISM

## A. MAGNETS AND MAGNETIC FIELDS.

A *magnet* has the following properties:—

1. If freely suspended, it will tend to set itself in a definite direction, one end pointing towards the north, the other end towards the south.

2. It attracts, and is attracted by, pieces of iron and steel, and deflects another freely suspended magnet from its position of equilibrium.

3. It has the power of enduing pieces of iron and steel in its neighbourhood with magnetic properties by 'induction.' Soft iron loses, steel retains its magnetism when the magnet is removed.

Iron, steel, magnetic oxide of iron ($Fe_3O_4$), nickel, and cobalt are *magnetics*, and are capable of being magnetized, and of being attracted by magnets, nickel and cobalt to a much less extent, however, than the others. It is probable that all other bodies, whether solids, liquids, or gases, are influenced by magnetism, but to such a small extent compared with those above mentioned that we may consider the rest as *non-magnetics*. Supports for magnets and magnetic apparatus are therefore made of brass, wood, glass, &c.

Magnets lose to a great extent their magnetic properties, if heated (see Experiment 12) or subjected to rough usage. On placing a magnet in iron filings and then withdrawing it, we notice that a bunch remains attached to each end and but very few to the middle. It appears therefore that the magnetic force is manifested most strongly near the ends and less towards the middle of the magnet. The points at which the greatest force is exerted are the so-called **poles** of the magnet.

**1. To determine the position of the so-called poles of a given magnet.**

*Apparatus.* A Bar Magnet: a Compass Needle[1]: a Drawing-board, on which a large piece of paper has been fixed with drawing-pins: a finely-pointed Pencil: a Half-metre Rule.

*Experiment.* Place the magnet in the middle of the drawing-board and, with a fine pencil, trace its outline on the paper. Place the compass on the right side of the magnet near one end, and mark by dots the positions of the ends of the needle when it comes to rest. Now transfer the compass to the left side of the magnet, and again mark the positions of the ends of the needle when at rest. The intersection of the straight lines joining the two pairs of points thus obtained, will indicate the projection of the pole of the magnet on the diagram. If we mark the ends of the needle when the compass is placed in different positions near one end of the magnet, we shall find that the straight lines joining the pairs of points will very approximately pass through the same point. Transfer the compass to the other end of the magnet, and determine, in a similar way, the position of the other pole.

When a magnet is freely suspended, the pole that points towards the north is called the *north-seeking* or *positive* or *marked* pole, the pole that points towards the south the *south-*

[1] The most convenient form of compass needle for this and subsequent experiments is one enclosed in a small circular box, the top and bottom of which are of glass. An aluminium wire is fixed to the middle of the needle exactly at right angles to its length.

*seeking*, *negative*, or *unmarked* pole. The two poles always occur in pairs, and we can never isolate one from the other, so that if we wish to study the effect of one pole only we have to use some means of neutralizing the effect of the other one (see Experiment 6).

If we bring an end of one magnet near an end of another magnet, which is freely suspended, we can show that

Like poles repel,
Unlike poles attract each other.

Accordingly the pole that points towards the north pole of the earth ought properly to be called the south pole. The north-seeking pole is an equally correct name for it, but we shall follow the usual custom and call it shortly the north pole.

The line joining the two poles is called the *magnetic axis*[2], and the vertical plane through the magnetic axis of a freely suspended magnet at rest under the earth's magnetic force alone is called the *magnetic meridian* of the particular place. The student should make a permanent mark upon the table, showing the direction along which a compass needle comes to rest, after all moveable pieces of iron or steel have been removed to a distance, so that he may know the direction of the magnetic meridian in the place in which he is working[3].

It has been stated above that the two poles always occur in pairs. This may be shown by breaking up a magnetized steel knitting-needle into small pieces. However small the pieces are, each will be found to be a perfect magnet having a north and a south pole—the north poles pointing in one direction, the south poles in the opposite direction. Upon this fact is based the theory that each molecule is a perfect magnet with a north and a south pole. This leads us to a more precise

[2] The magnetic axis does not in general coincide with the geometrical axis of symmetry of the magnet, but, except when great accuracy is required, we shall consider that the two do coincide.

[3] If there are any fixed pieces of iron or steel, e.g. gas brackets, heating stoves, &c., the needle will not lie along the true magnetic meridian, but along a direction imposed by the resultant action of the earth and of the magnetism induced by it in the fixed pieces. In all magnetic observations the student should remove from his person all keys, knives, &c.

definition of the poles of a magnet. 'Suppose the magnet placed in a uniform field[4], then the forces acting on the north poles will be a series of parallel forces acting in the same direction, and these by statics may be replaced by a single force acting at a point $P$, called the centre of parallel forces for this system of forces. This point $P$ is called the north pole of the magnet. Similarly the forces acting on the south poles may be replaced by a single force acting at a point $Q$, called the south pole of the magnet. The resultant force at $P$ is by statics the same as if the whole north polar charges were concentrated at $P$. This resultant is equal and opposite to that acting at $Q$.'[5]

*Magnetic Fields and Lines of Force.*—The space around a magnet in which the magnetic force is manifested is called its **magnetic field.** At any point in the field the force is completely specified when we know (*a*) its direction, (*b*) its intensity at the point. Place a bar magnet on the table and cover it with a piece of cardboard. Sprinkle some iron filings upon it from a muslin bag, gently tapping the cardboard meanwhile. The filings will arrange themselves in certain curved lines. Each filing has become by induction a little magnet, its north pole attracted towards the S. pole of the magnet, its south pole towards the N. pole of the magnet. The position of each filing shows the direction of the resultant magnetic force at its middle point. These lines are called **lines of force** and are by convention supposed to start from the north polar region of the magnet and to enter the south polar region, and to pass through the magnet, thus forming closed curves. No two lines of force can intersect, otherwise at the point of intersection the resultant force would have two different values, which is absurd. We may define a line of force as the direction along which an isolated north pole, if it were possible to have one, would move in its passage from the N. to the S. pole of the magnet, or we may say that the direction of a line of force at any point in the field is such that a compass

[4] For the definition of a uniform field, see p. 12.

[5] J. J. Thomson's *Elements of Electricity and Magnetism*, p. 190.

needle, when placed at this point, comes to rest tangentially to it.

**2. To plot the lines of force due to a given magnet.**

*Apparatus.* Same as in Experiment 1.

*Experiment.* Place the magnet in the middle of the drawing-board, and with a fine pencil trace its outline on the paper. Place the compass near one end, say the N. pole, of the magnet. The needle will come to rest under the resultant action of the earth and of the magnet. Move the board bodily round until the needle lies along the magnetic meridian so that its direction is controlled only by the magnet. Mark by dots the positions of the ends of the needle. Now move the compass further away, so that, when by moving the board as before the needle lies in the magnetic meridian, its south pole is exactly over the dot where its north pole was in its previous position. Mark the new position of its north pole. Continue this until the compass has reached the S. pole of the magnet. Draw a continuous curve through the mid-points of successive pairs of dots. This gives us one line of force. In a similar way mark out as many lines of force as you have time for, on both sides of the magnet, in each case starting from a different position near it. It will be found that one line is straight, viz. the one along the direction of the magnetic axis produced.

The lines of force so drawn are those in the section of the field made by the plane of the paper. Since the whole space surrounding the magnet is traversed by lines of force we ought to form an idea of the field as cut by surfaces of force.

As above plot the lines of force due to the following arrangements :—

(*a*) One bar magnet placed vertically so as to map out the field in a plane perpendicular to its axis.

(*b*) Two bar magnets placed parallel to each other (i) with like poles, (ii) with unlike poles adjacent.

(*c*) A horse-shoe magnet (i) without its keeper, (ii) with its keeper attached. The two fields in this case to be mapped

on the same paper, using red and black ink to distinguish them.

(*d*) The magnetic field of the working room, due to the resultant action of the earth and of the magnetism induced by the earth in fixed pieces of iron and steel in the neighbourhood.

(*e*) The field of a magnet, placed perpendicularly to the magnetic meridian, as distorted by the earth's force.

An **equipotential line** is one which is at every point perpendicular to the lines of force. Hence if we could move an isolated pole along an equipotential line, no work would be done by or against the magnetic forces. It is evident that no two equipotential lines can intersect each other, otherwise we could convey an isolated pole from one line of force to another line, where the force has a different value, by passing through the point of intersection of the two equipotential lines, without any work being done, which is absurd.

***3. To plot the equipotential lines of a magnetic field, and to prove that the work done in passing along a line of force between two given equipotential lines is the same in any part of the field.**

*Apparatus.* Same as in Experiment 1, and, in addition, a Magnetoscope[6]: a Stop-watch: a Half-metre Rule.

*Experiment.* Since the compass needle has a straight piece of aluminium wire fixed in the middle at right angles to its length, when the needle comes to rest in the magnetic field taking the direction of the line of force at the point, the position of the arm shows the direction of the equipotential line through this point. Keeping the drawing-board fixed, plot the lines of force, as in Experiment 2, of the resultant field due to the earth and the magnet. Then place the compass near one end of the magnet and, when the needle comes to rest, mark

[6] A magnetoscope is a short magnet suspended by a torsionless fibre of unspun silk, placed inside a glass specimen tube to shield it from air draughts. The end of the fibre is supported by a copper-wire hook passing through the cork closing the tube.

the positions of the ends of the arm. Move the compass into successive positions, so that one end of the arm is exactly over the dot made at the other end in its previous position. Finally, draw a continuous curve through the mid-points of successive pairs of dots. This gives us one equipotential line. In a similar way mark out as many equipotential lines as you have time for, in each case starting from a different position near the magnet. It will be found that they separate out from each other as they recede from the magnet, and are of an oval shape, becoming more and more circular as they approach the poles of the magnet. The one through the middle of the magnet is a straight line perpendicular to the axis. The equipotential lines so drawn are those in the section of the field made by the plane of the paper. Since the whole space surrounding the magnet is traversed by equipotential lines, we should form an idea of the field as cut by equipotential surfaces. They are ovoids, which become more and more spherical as they approach the poles of the magnet.

The work done by or upon an isolated pole in passing from one equipotential line to another along a line of force is equal to the product of the distance through which it moves by the average magnetic force along the path. It will be shown subsequently (p. 36) that the forces exerted by two uniform magnetic fields are proportional to the squares of the number of vibrations made in the same time by a compass needle placed successively in the two fields. Place the magnetoscope midway between two equipotential lines on one of the marked lines of force. Displace the needle from its position of equilibrium, and, with a stop-watch, note the time taken by it to make twenty vibrations[7]. Take the time of another twenty vibrations, and, if the two observed times do not differ by more than three-fifths of a second, take the average[8], and calculate the number of

[7] If we consider only a small portion of a magnetic field we may without appreciable error assume that the lines of force within this area are parallel. Since the needle is small we may therefore consider the portion of the field in which it swings to be uniform (see p. 12). The region experimented in must not be too near the magnet nor must the equipotential lines be too far apart.

[8] If there is a greater difference, we must repeat the experiment and take the average of the times that differ least from each other.

vibrations, $n_1$, that the needle would make in a minute. Measure the distance, $l_1$, between the two equipotential lines along the line of force on which the magnetoscope is placed. Now transfer the magnetoscope to another line of force midway between the same two equipotential lines. As before, find the number of vibrations, $n_2$, the needle would make in a minute, and measure the length, $l_2$, of the line of force between the two equipotential lines. Make a third set of observations in another part of the field between the same two equipotential lines, and enter your results in a tabular form as follows:—

| Average magnetic force varies as $n^2$ | Length of the line of force between the two equipotential lines $l$ | Work done varies as $n^2 l$ |
|---|---|---|
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |

The numbers in the third column will be found to be constant, proving what is required.

Coulomb proved by his torsion balance that the force, $f$, between two magnetic poles varies inversely as the square of the distance, $d$, between them. If one pole remains fixed, a second pole will at a given distance exert a definite force on it. If now another pole placed at the same distance exerts twice or thrice the force, we say the strength of this pole is twice or thrice as great. Thus the force between two poles also varies as the product of the two pole-strengths $m$, $m'$.

$$\therefore \quad f \propto \frac{m\,m'}{d^2}, \text{ (see footnote).}$$

or by Algebra $$f = K\frac{m\,m'}{d^2},$$

where $K$ is some constant number depending on the units employed to express the different quantities. Now the unit

[1] We consider only air as the medium.

of force is the *dyne*[10], the unit of distance a *centimetre*, the only undefined unit in the above expression being that of magnetic pole-strength. For simplicity let us define unit pole-strength to be the strength of either of two equal poles which, when placed 1 cm. apart, exert a force of 1 dyne upon each other. With this definition $K$ becomes unity, and the force between two poles of strengths $m$, $m'$, placed $d$ centimetres apart, is

$$f = \frac{m\,m'}{d^2} \text{ dynes.} \tag{i}$$

In the case of a magnet, as it consists of two poles of opposite sign, the resultant force upon a single pole will be the resultant of the forces exerted by each of the two poles. Suppose a very long magnet $B$, of pole-strength $m'$, is placed so that its axis is in the same straight line as the axis of another magnet $A$, of pole-strength $m$ and length $l$, with the north poles of each facing, and at a distance $h$ from, each other. The resultant force exerted by the magnet $A$ upon the north pole of $B$ is very approximately equal to the difference between the repulsive force of the north pole and the attractive force of the south pole of $A$, and is given by

$$f = m\,m'\left(\frac{1}{h^2} - \frac{1}{(h+l)^2}\right) \text{ dynes.} \tag{ii}$$

Again, the force, $f'$, with which a magnetic field acts upon a magnetic pole placed at a given point in it, varies

(i) as the strength of the pole, $m$;

(ii) as the intensity, $F$, of the magnetic field at the point;

$$\therefore \quad f' \propto mF.$$

Defining, in the same way as above, that field to be of unit intensity which exerts a force of one dyne upon a unit pole, the force which a field of intensity, $F$, exerts upon a pole of strength, $m$, is

$$f' = m\,F \text{ dynes.} \tag{iii}$$

[10] A dyne is that force which, acting upon a mass of one gram, produces an acceleration of 1 cm. per second every second. Since the weight of one gram produces in it an acceleration of 980 cm. per sec. per sec., a dyne $= \frac{1}{980}$th of the weight of one gram. It is thus nearly equal to the weight of a milligram.

*The intensity of a magnetic field is therefore the force exerted by it on a pole of unit strength.*

A **uniform magnetic field** is one in which the lines of force are parallel to each other. The earth's field at a given place may be considered uniform, since its lines of force are practically parallel within the room in which we are working. There are, of course, an infinite number of lines of force in a magnetic field, but if we consider only so many lines of force to pass through 1 sq. cm. placed perpendicularly to their direction as is indicated by the force in dynes at a given point of the field, then the force at any other point will be represented by the number of these lines which pass through 1 sq. cm. placed perpendicularly to their direction at this point. Since the horizontal intensity of the earth's magnetic force (see p. 16) is ·18 dynes approximately, 18 lines of force are taken to pass through an area of 100 sq. cm. placed perpendicular to the magnetic meridian.

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## B. Earth's Magnetism.

### The Angle of Declination.

The magnetic meridian of a given place does not in general coincide with its geographical meridian. The angle between the two is called the *angle of declination*. This angle varies in different places, and also from year to year at the same place[11]. The following table gives its average values for the different years at London:—

| | | | |
|---|---|---|---|
| 1580 | 11° 17′ E | 1816 | 24° 30′ W |
| 1634 | 4° 0′ E | 1868 | 20° 33′ W |
| 1657 | 0° 0′ | 1882 | 18° 22′ W |
| 1705 | 9° 0′ W | 1889 | 17° 35′ W |
| 1760 | 19° 30′ W | 1894 | 17° 23′ W |

[11] It also undergoes smaller variations at different seasons of the year and at different hours of the day. Temporary variations of larger magnitude occur during 'magnetic storms.'

We see that the angle of declination oscillates from east to west and back, the maximum angle being between 24° and 25°, and that in 1657 it was 0°, i.e. in that year the needle in London pointed along the geographical meridian, due N. and S.

**4. To determine the magnetic axis of a uniformly magnetized circular steel disk.**

*Apparatus.* A uniformly magnetized circular Steel Disk with a double hook through its centre so that it can be suspended from either face: a Circle of somewhat larger diameter than the disk, graduated from 0° to 180° the same way round the two semi-circumferences: a Wooden Clamp.

*Experiment.* Mark two straight lines, one on each face of the disk, passing through its centre, so that both end at the same points on the circumference. Suspend the disk by a torsionless thread from a wooden support, the point of suspension being as nearly as possible over the centre of the graduated circle. Read the angles over which the two ends of the line drawn on the upper face come to rest. Reverse the faces of the disk, and again read the angles over which the ends of the line now uppermost come to rest. The mean of the four angles will be the angle made by the magnetic axis with the line of zeros, assuming this line to have been fixed approximately north and south.

(i) Since the disk is uniformly magnetized, its magnetic axis passes through its centre, and, since it always lies in the same direction, whichever face of the disk is uppermost, the end of one of the marked lines will be as much on one side of the axis as the same end of the other line is on the other side of the axis when the disk is reversed. The average of the two angles is the angle which the magnetic axis makes with the line of zeros, provided the centre of the disk is exactly over the centre of the graduated circle.

(ii) Suppose the centre of the disk $C'$ (Fig. 1) is not exactly over the centre $C$ of the graduated circle. Let $MM'$ be the magnetic axis. The arc $OM$ is subtended by the angle $OCM$, the arc $O'M'$ by the angle $O'CM'$ or $OCM''$. Hence

the angle the magnetic axis would make with the line of zeros if the disk were suspended as the centre of the circle is the average of the angles made by the two ends of the axis.

Hence the average of the four angles above read fixes the position of the magnetic axis of the disk.

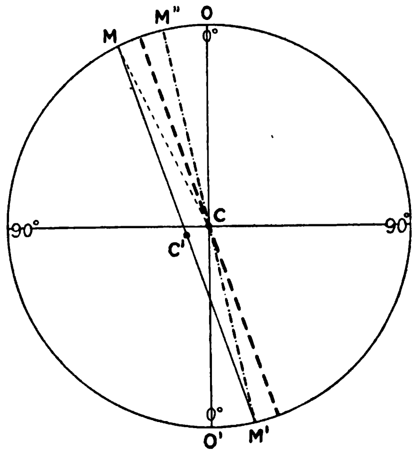


Fig. 1.

In determining accurately the magnetic meridian by a compass needle, the average of four angles is taken, viz. the readings of both ends of the compass needle before and after reversing its faces. By this means the two possible errors are eliminated—

(i) that in general the magnetic axis does not coincide with the axis of symmetry of the needle;

(ii) that the needle is not suspended exactly at the centre of the graduated circle.

### The Angle of Inclination or Dip.

With a compass needle or a magnet suspended on a vertical axis so that it swings in a horizontal plane we can determine the magnetic meridian, i. e. the vertical plane in which the earth's force acts. To determine the line in this plane along

which the total earth's force acts we have to use a dip-needle, i. e. a needle supported on a horizontal axis, so that it swings in a vertical plane. Pass an unmagnetized knitting-needle through a cube of cork. In the centre of two opposite faces of the cube stick two sewing-needles perpendicular to the knitting-needle. Rest the two needles on two pieces of glass tubing fixed horizontally in a wooden clamp and parallel to each other at a convenient distance apart. Move the cube until the two needles pass through the centre of gravity of the knitting-needle. When this is the case the latter will rest in any position. Turn the apparatus round until the knitting-needle lies along the magnetic meridian in a horizontal position. Take it off and magnetize it. On replacing it, we shall find it come to rest at an angle to the horizontal—its N. pole pointing downwards in the northern hemisphere. It lies now in the direction of the total earth's magnetic force. The angle it makes with the horizontal is called the *angle of inclination* or *dip*. This angle varies in different latitudes, increasing as we pass from the magnetic equator[12] towards the north or south magnetic pole of the earth—the N. pole of the needle pointing downwards in the northern hemisphere, the S. pole pointing downwards in the southern hemisphere. The angle also varies from year to year in the same place (see note 11). The following table gives its average values for the different years at London:—

| | | | |
|---|---|---|---|
| 1576 | 71° 50′ | 1828 | 69° 47′ |
| 1676 | 73° 30′ | 1854 | 68° 31′ |
| 1723 | 74° 42′ | 1874 | 67° 43′ |
| 1800 | 70° 35′ | 1894 | 67° 24′ |

### *5. To determine the angle of dip.

*Apparatus.* A Dip-circle: two Bar Magnets.

*Experiment.* The dip-circle is a graduated circle with its plane vertical and the line of zeros horizontal, through the

[12] The *magnetic equator* is the line passing through places on the earth's surface at which the dip-needle rests horizontally, i.e. where the angle of dip is 0°. It follows approximately the geographical equator, but does not coincide with it.

centre of which is pivoted a magnetic needle on a horizontal axis. The total intensity, $T$, of the earth's field can be resolved into two components at right angles to each other in the magnetic meridian, one horizontal called the horizontal intensity, $H$, the other vertical called the vertical intensity, $V$. When the plane of the dip-circle is not in the magnetic meridian, the angle which the needle makes with the horizontal is greater than the angle of dip, since a portion of the horizontal component is counteracted by the pivots. When the dip-circle is exactly perpendicular to the magnetic meridian, the whole of the horizontal component is counteracted by the pivots, and the vertical component, which now is the only one that affects the needle, causes it to point vertically downwards. We can thus determine the magnetic meridian with the dip-circle in two ways.

(i) Move it round till the angle which the needle makes with the horizontal is a minimum.

(ii) Move it round till the needle points vertically downwards and then turn it through a right angle.

Through the middle of the base-board of the dip-circle draw two straight lines at right angles to each other. Turn the instrument till the needle points vertically downwards and mark on the table the positions of the extremities of the lines. On turning the base-board through a right angle the needle swings in the magnetic meridian. To get the true angle of dip we have to eliminate three possible errors.

(i) The needle may not be pivoted at the centre of the circle; therefore read both ends of the needle.

(ii) The magnetic axis of the needle may not coincide with its axis of symmetry; therefore reverse the faces of the needle and again read both ends.

(iii) The needle may not be suspended through its centre of gravity. This error is eliminated by remagnetizing the needle, so as to reverse its polarity, and repeating the above observations. The centre of gravity after reversal of the polarity

is as much on one side of its axis of suspension as it was on the other side before reversal. Therefore gravity increased the observed angle of dip when the centre of gravity was below the axis, just as much as it decreased the angle when the centre of gravity was above the axis. The average of the above eight angles gives therefore the true angle of dip.

If we determine $H$, the horizontal intensity [Experiment 15], and $\phi$, the angle of dip, the total intensity, $T$, of the earth's field is evidently given by

$$\frac{H}{\cos\phi}.$$

---

## C. Action of one Magnet on another.

The earth's horizontal component is not translational but simply directive, i.e. it only tends to twist a freely suspended magnet around its vertical axis until it lies along the magnetic meridian. This can be shown by floating a magnet on a piece of cork in a dish of water. The magnet will turn so as to lie along the meridian, but will not be pulled towards the sides of the dish. The forces on either pole are therefore equal and opposite and parallel to each other. Such a pair of forces is called a 'couple.' The measure of the *torque* or the pull which the earth exerts on the needle tending to bring it back to the meridian is given by the 'moment of the couple,' i.e. the product of one of the forces by the perpendicular distance between them. Let the needle *n s* (Fig. 2) be deflected an angle *a* from the

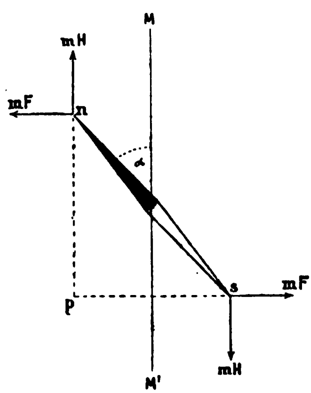

Fig. 2.

meridian $MM'$. The force on either pole is $mH$ dynes (Equation iii), where $m$ is the pole-strength and $H$ the horizontal intensity of the earth's field. The moment of the earth's couple is

$$mH \times sp = mHl \sin a,$$

where $l$ is the length of the magnetic axis of the needle. Not knowing the exact position of the poles we cannot in general determine $m$ and $l$ separately. The product $ml$, called the **moment** of the magnet, and indicated by the letter $M$, we can measure (Experiment 15). Substituting we get the moment of the couple to be

$$MH \sin a.$$

Hence we can define the moment of a magnet to be the torque exerted upon it when placed at right angles to the lines of force in a field of unit intensity. The torque is thus greater (*a*) the greater the pole-strength of the magnet, since the force acting upon it varies as the pole-strength, (*b*) the greater the length of the magnet, since there is greater leverage. If the needle is kept deflected at the angle $a$ from the meridian by the action of another uniform field of intensity, $F$, whose lines of force are perpendicular to the meridian, the force exerted by it on either pole is $mF$ dynes. The moment of this couple is

$$mF \times np = mFl \cos a.$$

Since the needle is supposed to be at rest, the torques of the two couples, one tending to pull it back to, the other to deflect it still further from the meridian, must be equal;

$$\therefore \quad mFl \cos a = mHl \sin a$$

$$\text{or} \quad F = H \tan a. \qquad \text{(iv)}$$

This expresses what is termed the 'tangent law,' which may be enunciated as follows:—

*If a uniform magnetic field, whose lines of force are perpendicular to the magnetic meridian, deflects a compass needle so that it comes to rest at an angle to the meridian, the ratio of the intensity of this field to that of the earth's field is equal to the tangent of the angle of deflexion.*

We thus see that the angle of deflexion does not theoretically depend upon the pole-strength of the needle, but if the latter is suspended on a pivot, the greater the pole-strength the more easily is the friction of the pivot overcome.

Since $\tan 45^\circ = 1$, the intensity of such a field, causing a deflexion of $45^\circ$, is equal to that of the earth's field.

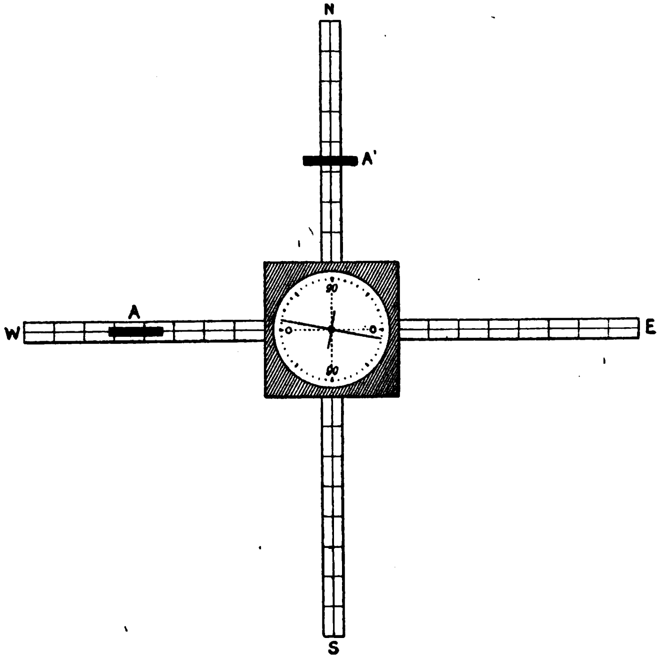


Fig. 3.

**The Magnetometer** (Fig. 3) consists of a circle enclosed in a square box with a glass cover. The four quadrants of the circle are graduated from $0^\circ$ to $90^\circ$ in such a way that the zeros are in the same straight line. The circle is pasted on a plane mirror, a part of which is exposed by cutting out a circular band between the centre and the circumference. At the centre is pivoted or suspended a short magnetic needle, to the middle of which, at right angles to its length, is fixed

a light pointer of glass thread or aluminium wire. The ends of the pointer move over the graduated circle, and thus we are enabled to read the angle of deflexion of the short needle. The circle is fixed so that the line of zeros is at right angles to two opposite sides of the box and a straight line is cut on the glass cover exactly over the line joining the 90° divisions. Four arms, graduated in millimetres, are attached at right angles to each side of the box, the graduations of each arm starting from the centre of the circle.

Before using the instrument we must turn it round until the needle comes to rest with its axis exactly under the line cut on the glass cover, which line is then in the magnetic meridian. The pointer, if exactly at right angles to the needle, now lies along the line of zeros. When the instrument has been thus adjusted we shall call the four arms respectively the N., S., E., W. arm, according to the directions in which they point. The ends of the pointer appear in different positions according to the direction in which we look at them. This is due to 'parallax,' and to avoid it when reading an angle we must always place our eye above the box in such a position that the pointer covers its own reflexion in the mirror. If the magnet is pivoted it is well to tap the instrument gently so that the needle takes up its proper position.

**6. To prove that the intensity of the field at a given point, due to a single magnetic pole, varies inversely as the square of the distance between that point and the pole.**

*Apparatus.* A long, thin Magnet or Magnetized Steel Knitting-needle, about 30 cm. long: Magnetometer: a Wooden Clamp.

*Experiment.* Adjust the magnetometer properly. Support the magnet so that one end, held in or more conveniently hinged to the wooden clamp, is exactly over the centre of the circle, the other end resting on, say, the E. arm. Though we cannot in practice have an isolated magnetic pole, yet by the above arrangement we can study the effect of one pole on the

needle, since the one suspended over the centre does not sensibly influence the deflexion. The needle is now deflected and takes up a position of equilibrium at an angle to the meridian, due to the resultant effect of the earth's field and that of the single pole of the magnet. Since the needle is short and its distance from the pole is great compared with its length, the field, due to the latter, in which it moves, may be taken to be uniform and the forces on the poles of the needle, the one attractive the other repulsive due to the single pole, to be equal, parallel, and in opposite directions. Hence the intensity of the field varies as the tangent of the angle of deflexion (Equation iv). Note the distance, $d$, of the pole from the centre of the circle, and read the angles made by each end of the pointer. Transfer the pole to the W. arm at exactly the same distance from the centre and again read the ends of the pointer. The average of the above four angles[13] will be the true angle, $a$, of deflexion produced by the pole at this distance, $d$. Repeat the above observations, varying the distance between the pole and the centre by altering the height of the clamp, in each case being careful to adjust the suspended pole exactly over the centre. If the strength of the magnet allows, deflexions should be obtained about every five degrees between 20° and 60°. Enter your results in a tabular form as follows:—

| Pointer | | | | Average angle of deflexion $a$ | Field intensity at centre varies as tan $a$ | Distance of pole from centre $d$ | $d^2$ | $d^2 \times$ tan $a$ | Field intensity at centre in dynes $F$ |
|---|---|---|---|---|---|---|---|---|---|
| End $A$ | | End $B$ | | | | | | | |
| E | W | E | W | | | | | | |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

[13] In determining the angle of deflexion of a needle the average of four angles should always be taken, viz. the angles made by the two ends of the pointer when deflected on opposite sides of the line of zeros under the same conditions. This neutralizes the errors due to the needle not having been originally exactly in the magnetic meridian and not being pivoted exactly at the centre of the graduated circle.

The field intensities in the last column are found from $F = H \tan a$, taking $H = \cdot 18$.

The numbers in the last column but one will be found to be approximately constant, proving what is required. It will be seen that this constancy is the more noticeable the nearer the angle of deflexion is to $45^\circ$, since the further from $45^\circ$ the greater is the percentage error in the tangent due to a wrong reading. Thus supposing an error of observation of half a degree is made when the deflexion is $25^\circ$, $45^\circ$, $65^\circ$ respectively—

| | | | |
|---|---|---|---|
| | tan 25·5 = ·4770 | tan 45·5 = 1·0176 | tan 65·5 = 2·1943 |
| | tan 25·0 = ·4663 | tan 45·0 = 1·0000 | tan 65·0 = 2·1445 |
| Difference | = ·0107 | ·0176 | ·0498 |
| % error | = 2·3 | 1·76 | 2·3 |

**7. To show that the law of the inverse square of the distance agrees with experiment.**

*Apparatus.* Same as in Experiment 1.

*Experiment.* There are two methods by which we can establish the so-called laws of science: one by proving them, if possible, by experiment, the other by showing that, with the assumption of their being true, they lead to phenomena which agree with experiment[14]. We shall now adopt the second method to prove that the force between two magnetic poles varies inversely as the square of the distance between them. Place the magnet in the middle of the drawing-board and with a fine pencil trace its outline on the paper and mark the positions of its two poles N. and S. Remove the magnet. Suppose a south pole placed at any point $P$ in the magnetic field (Fig. 4) and join $PN$ and $PS$. Measure these distances accurately. Along $PN$ mark off a length, $Pa$, proportional to $\frac{1}{PN^2}$, and along $PS$ produced, a distance $Pb$ proportional on the same scale to $\frac{1}{PS^2}$. By the parallelogram of forces the resultant force at $P$ will lie along $Pc$, the diagonal through $P$

[14] The truth of the Laws of Gravitation, Avogadro's Law, and the validity of the Atomic Theory and the Undulatory Theory of Light are established by the second of these methods.

of the parallelogram built upon $Pa$, $Pb$, as adjacent sides, and this will therefore be the direction along which a compass needle will lie, under the action of the magnet, when its centre is at $P$. Move the board bodily round till $Pc$ is parallel to the magnetic meridian. Replace the magnet exactly in its original position on the board. A compass needle, with its centre at $P$, will be found to lie along $Pc$. The direction of the resultant force at any point $P$ can be found as follows. Join $P$ to the mid-point $O$ of the magnet, and trisect $PO$ at $Q$. Through $Q$ draw $QT$ at right angles to $PO$, cutting the axis of the magnet produced at $T$. Join $PT$. Then $PT$ is the direction required. Gauge the accuracy of your measures by applying this method.

Repeat the above at two other points in the field.

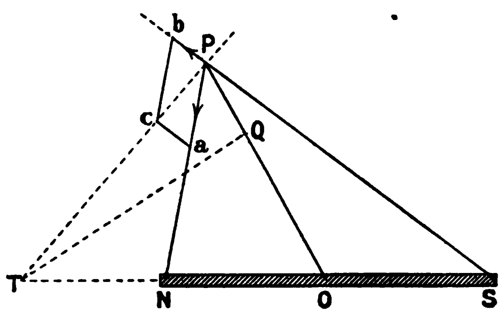


Fig. 4.

**8. To illustrate the tangent law experimentally and to determine the pole-strength of a given magnet.**

*Apparatus.* Three Bar Magnets, $A$, $B$, $C$, about 10 cm. long: Magnetometer.

*Experiment.* Adjust the magnetometer properly. Place the magnet $A$ on the W. arm with its N. pole pointing E., at such a distance that it causes a deflexion of exactly 45°. The intensity of the field at the centre due to the magnet is equal to that of the earth, or $F = H$ (p. 19). Now place the magnet $B$ on the E. arm with its N. pole pointing W., at such a distance that the needle returns exactly to the magnetic meridian. The fields of $A$ and $B$ are opposed to each other, and since the needle is

undeflected they must be of equal intensity, i.e. the intensity of the field due to *B* at the centre is equal to that of the earth.

Reverse *B*, placing its S. pole towards the W. exactly at the same distance as its N. pole was from the centre. The fields of *A* and *B* now act in the same direction, and the intensity of the resultant field should be twice that of the earth. The needle is seen to be deflected 63° 26′, the tangent of which is 2. Hence $F = 2\,H$.

Repeat the above, using *A* and *C*, and again with *B* and *C*. To determine the pole-strength of *A* place it on the W. arm at such a distance as to produce an angle of deflexion about 30°. Read both ends of the pointer. Find the length, $l$, of the magnet, and the distance, $h$, of the centre of the circle from the nearer pole. Transfer the magnet to the E. arm, reversing its poles, at exactly the same distance from the centre, and read the ends of the pointer. The average, $a$, of the four angles will be the angle of deflexion corresponding to the given distance. Taking $H$ as ·18 find $F$ from Equation (iv). Putting $m' = 1$ in Equation (ii) the intensity of the field is given by

$$F = m\left(\frac{1}{h^2} - \frac{1}{(h+l)^2}\right).$$

Substituting in it for known quantities we can determine on the pole-strength of the magnet.

Repeat the above twice more, getting angles of deflexion about 45° and 60°, and enter your results in a tabular form as follows:—

| Pointer | | | | Average angle of deflexion $a$ | tan $a$ | $F$ | $m$ |
|---|---|---|---|---|---|---|---|
| End *A* | | End *B* | | | | | |
| E | W | E | W | | | | |
| ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... |

Find the pole-strengths of *B* and *C* as above.

**Resultant action of a magnet upon a magnetic pole.**

(*a*) *The end-on position.*

Let *NS* (Fig. 5) be a magnet of length $2\,l$, the mid-point of

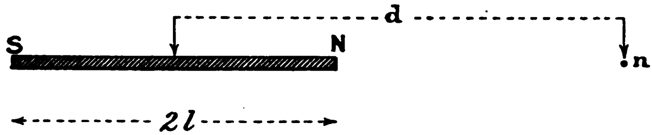


Fig. 5.

which is at a distance, *d*, from a north pole of unit strength at *n*, a point in the continuation of the axis of the magnet. The intensity of the resultant field at the point *n* is the difference between the repulsive force of *N* and the attractive force of *S* upon the unit pole at *n*, and is given by

$$F = m\left[\frac{1}{(d-l)^2} - \frac{1}{(d+l)^2}\right] = \frac{4\,m\,d\,l}{(d^2-l^2)^2},$$

$$\text{or} \quad F = \frac{2\,Md}{(d^2-l^2)^2}, \qquad \text{(v)}$$

where $\mathrm{M} = 2\,m\,l$ the moment of the magnet *NS*.

If now we place a short magnetic needle at *n*, the axis of *NS* being perpendicular to the magnetic meridian and passing through the centre of the needle (in the end-on position as at *A* in Fig. 3), we may take it that, if the distance *d* is great compared with the length of the needle, the portion of the field in which the latter swings is uniform, and if the magnet produces an angle of deflexion, $a$,

$$\mathrm{F} = H \tan a.$$

Equating the two values for *F*, we have

$$\frac{M}{H} = \frac{(d^2-l^2)^2 \tan a}{2d}. \qquad \text{(vi)}$$

N.B. We may put (v) in the form $F = \dfrac{2M}{d^3\left(1 - \dfrac{l^2}{d^2}\right)^2}$,

and if $d$ is great compared with $l$ (i.e. if we use a very short magnet), $\frac{l^2}{d^2}$ may be neglected, and

$$F = \frac{2M}{d^3} \tag{vii}$$

$$\text{and} \quad \frac{M}{H} = \frac{d^3 \tan \alpha}{2}. \tag{viii}$$

In order that this equation should have an error of less than $1\%$, $\frac{l}{d}$ must be less than $\frac{1}{17}$.

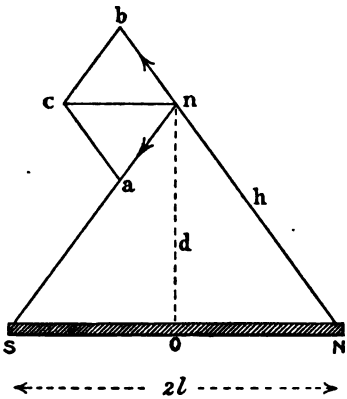


Fig. 6.

($\beta$) *The broad-side position.*

Let $NS$ (Fig. 6) be a magnet of length $2l$, the mid-point of which is at a distance, $d$, from a north pole of unit strength at $n$, in such a position that the straight line joining $n$ to the mid-point of the magnet is perpendicular to the axis of the latter. Let $m$ be the strength of either pole of the magnet. The repulsive force of $N$ and the attractive force of $S$ on the unit pole at $n$ are each equal to

$$\frac{m}{h^2} = \frac{m}{d^2 + l^2},$$

where $h$ is the distance of $n$ from $N$ or $S$.

Along $nS$ and $nN$ produced mark off equal lengths $na$, $nb$, to represent these forces and complete the parallelogram. The resultant force $F$ on the unit pole will on the same scale be given by the diagonal $nc$, parallel to the axis of the magnet. Since the triangles $cna$ and $nSN$ are equiangular,

$$\frac{nc}{na} = \frac{NS}{nS} \quad \text{(Eu. vi. 4)},$$

$$\therefore \quad F = \frac{2ml}{(d^2+l^2)^{3/2}} = \frac{M}{(d^4+l^2)^{3/2}}, \qquad \text{(ix)}$$

where $M = 2ml$ the moment of the magnet $NS$.

If now we place a short magnetic needle at $n$, the axis of $NS$ being perpendicular to the magnetic meridian, but in this case the line joining the centre of the needle to the mid-point of the magnet being perpendicular to the axis of the latter (in the broad-side position as at $A'$ in Fig. 3), we may take it that under the same conditions as before each of the forces on the poles of the needle, if of unit strength, is equal to the above expression. If, again, the magnet produces an angle of deflexion, $\alpha'$,

$$F = H \tan \alpha'.$$

Equating the two values we have

$$\frac{H}{M} = (d^2+l^2)^{3/2} \tan \alpha'. \qquad \text{(x)}$$

N.B. If $d$ is great compared with $l$, (vii) becomes

$$F = \frac{M}{d^3}, \qquad \text{(xi)}$$

$$\text{and} \quad \frac{M}{H} = d^3 \tan \alpha'. \qquad \text{(xii)}$$

The above two positions of the magnet relatively to the needle are called the 'principal positions.' The formulae (vi) and (x) are approximate only as the dimensions of the needle, unless infinitely short, affect them, and $l$ should be the length of the magnetic axis instead of the length of the magnet. We see from (vii) and (xi) that in each position the force varies inversely

as the cube of the distance of the centre of the needle from the mid-point of the magnet, and that if this distance is the same in the two positions of the magnet, the field in the end-on position has double the intensity of that in the broad-side position when the angle of deflexion is the same. To prove this, place a short magnet on the N. arm in the broad-side position at such a distance as to produce an angle of deflexion 45°, whose tangent is 1. Transfer the magnet to the E. or W. arm so that the distance of its mid-point is exactly the same as before. We shall find the deflexion is 63° 26′, whose tangent is 2.

It can be shown that this result only obtains if the force between two magnetic poles varies inversely as the square of the distance between them—in fact this and the following experiment are the only rigid experimental proofs of the law of the inverse square for magnets.

**9. To prove that the intensity of the field produced at a point by a short magnet in either of the two principal positions varies inversely as the cube of the distance between the point and the mid-point of the magnet.**

*Apparatus*. A short Magnet about 2 cm. in length: Magnetometer.

*Experiment.* Adjust the magnetometer properly. Place the magnet on the W. arm with its N. pole pointing eastward at such a distance that it produces an angle of deflexion about 60°. Note the distances of its two poles from the centre, and take the average to get the distance, $d$, of its mid-point. Read the ends of the pointer. Transfer the magnet to the E. arm, at exactly the same distance from the centre as before, and reverse the poles. Read the ends of the pointer. Take the average of the four angles as the angle of deflexion, $\alpha$, corresponding to the distance, $d$. Repeat the above moving the magnet successively further from the centre, in each case noting the distance of its mid-point, and the corresponding average angle of deflexion, until if possible the deflexion is reduced to about 25°. Enter your results on a similar plan to that given on p. 21.

Now take a similar set of observations, placing the magnet in

the broad-side position. Care must always be taken that the length of the magnet is perpendicular to and is bisected by the magnetic meridian. The distance, $d$, is the distance between the mid-point of the axis and the centre, which may be found by taking the average of the distances of the two sides from the centre.

The product $d^3 \tan \alpha$ will in each case be found to be approximately constant, the more so the less the angle of deflexion differs from 45° (p. 22), proving what is required.

**10. To compare the moments of two short magnets by the magnetometer.**

*Apparatus.* Two short Magnets: Magnetometer.

*Experiment.* (Method 1. *For constant angle.*) From Equations (viii) and (xii) we see that in a given place, i.e. $H$ being constant, the moment, $M$, of a short magnet varies as $d^3 \tan \alpha$ in both principal positions. Hence the moments of two such magnets are proportional to the cubes of their mid-points from the centre, at which either produces the same angle of deflexion. Adjust the magnetometer properly. Place one of the magnets on the W. arm with its N. pole pointing eastwards, so that it produces a deflexion between 50° and 60°, and note the distance, $d$, of its mid-point from the centre. Place the other magnet on the E. arm with its N. pole pointing westwards, so that the fields of the two magnets are opposed to each other, and move it till the needle returns exactly to the meridian. Note the distance, $d_1$, of its mid-point from the centre. It is evident that either magnet alone would produce the same angle of deflexion. The moments of the two magnets are proportional to the cubes of the above distances. Repeat the above twice more, in each case altering the distances of the magnets from the centre, and enter your results in a tabular form as follows:—

| $d$ | $d^3$ | $d_1$ | $d_1^3$ | $\frac{M}{M_1} = \frac{d^3}{d_1^3}$ |
|---|---|---|---|---|
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |

(Method 2. *For constant distance.*) The moments are also proportional to the tangents of the angles of deflexion produced by either magnet separately when their mid-points are at the same distance from the centre. Place the weaker of the two magnets on the W. arm so as to produce a deflexion of about 40°, and note the distance of its mid-point from the centre. Read the ends of the pointer. Reverse the poles of the magnet, and transfer it to the E. arm at exactly the same distance from the centre as before. Take the average as the angle of deflexion, $\alpha$. Replace this magnet by the other one and repeat the above, being careful that the distance between its mid-point and the centre is the same as before. Let $\acute{\alpha}$ be the average angle of deflexion. Enter your results in a tabular form as follows:—

| End of pointer | Magnet 1 | | | | Magnet 2 | | | $\frac{M}{M_1} = \frac{\tan \alpha}{\tan \alpha_1}$ |
|---|---|---|---|---|---|---|---|---|
| | | | $\alpha$ | $\tan \alpha$ | | $\alpha_1$ | $\tan \alpha_1$ | |
| A | E | ... | | | ... | | | |
| | W | ... | | | ... | | | |
| B | E | ... | ... | ... | ... | ... | ... | ... |
| | W | ... | | | ... | | | |

Compare your results for $\frac{M}{M_1}$. If the magnets are of equal lengths this also gives the ratio of their pole-strengths.

***11. To find the relation between the radial position of a magnet and the deflexion it produces on a compass needle placed at the centre of the circle.**

*Apparatus.* A Bar Magnet: Magnetometer with the arms removed: a pair of Blackboard Compasses: Curve Paper: a Metre Rule.

*Experiment.* Fix a large sheet of paper to the table, and describe two or three concentric circles with radii varying from 20 to 80 cm. Place the magnetometer so that the centre coincides with the centre of the circles drawn, and adjust it properly.

Mark the position of the magnetic meridian, remove the magnetometer, and draw two diameters at right angles to each other, one along the magnetic meridian, the other perpendicular to it. Now by the method of Eu. i. 1 divide the circles in angles differing by $30^\circ$ all the way round, and mark them from $0^\circ$ to $360^\circ$, the $0^\circ$–$180^\circ$ line being along the meridian. Replace the magnetometer in its previous position. Place the magnet along the meridian with its mid-point at the $0^\circ$ division of one of the circles at a sufficiently great distance from the needle, so that when two similar poles are adjacent, the needle is not turned round. Move the magnet round the circle $30^\circ$ at a time, so that it always lies along a radius, keeping its mid-point on the circumference. Note the angular positions of the magnet and the corresponding angles of deflexion of the needle. The latter must be taken as + on one side of the line of zeros and − on the other side. Enter your results in a tabular form as follows:—

| Angular position of magnet $\theta$ | Angle of deflexion of needle $a$ |
|---|---|
| ... | ... |
| ... | ... |

Plot a curve with the angular positions of the magnet as abscissae, and the angles of deflexion as ordinates. Now reverse the poles of the magnet, and repeat the above experiment, and plot another curve on the same sheet of paper.

As an additional experiment move the magnet round the circle, with its centre upon the circumference, but with its axis always perpendicular to the magnetic meridian, and plot a curve connecting the positions of the magnet and the corresponding angles of deflexion.

The moment of a magnet decreases as its temperature rises. The mean coefficient of decrease $a$ for a given rise of temperature is that decrease which a magnet, having unit moment at the

lower temperature, undergoes when heated through the given range, or if $M_T$, $M_t$ be the moments of a magnet at $T^\circ$ and $t^\circ$ respectively,

$$a = \frac{M_T - M_t}{M_t(T-t)} = \left(\frac{M_T}{M_t} - 1\right) \div (T-t).$$

***12. To determine the average coefficient of decrease in the moment of a short magnet for a given rise of temperature.**

*Apparatus.* Two short Magnets: Magnetometer: a shallow Glass Vessel in which one of the Magnets is to be heated: Thermometer.

*Experiment.* Adjust the magnetometer properly. Place one of the magnets, resting in the glass vessel nearly full of oil, on the W. arm, so that its N. pole points eastwards at such a distance from the centre as to produce an angle of deflexion between 40° and 50°. Read the distance, $d$, of its mid-point from the centre. Place the other magnet on the E. arm with its N. pole pointing westwards, and move it until the needle returns exactly to the magnetic meridian. Read the distance, $d$, of its mid-point from the centre. Note the temperature, $t$, of the oil.

If $M_t$ is the moment of the magnet in the oil at $t^\circ$, $M$ is the moment of the other magnet.

$$\frac{M_t}{M} = \frac{d^3}{d_1^3}. \qquad \text{(xiii)}$$

Now heat the oil to about 140°, and replace the vessel on the W. arm, so that the magnet is in exactly the same position as before. Since the moment decreases as the temperature rises, we have to move the other magnet further away, until the needle again lies along the meridian, and read the distance, $d_2$, of its mid-point from the centre, and simultaneously the temperature, $T$, of the oil, which we may take as the temperature of the magnet immersed. If $M_T$ be the moment of the latter at $T^\circ$,

$$\frac{M_T}{M_t} = \frac{d^3}{d_2^3}. \qquad \text{(xiv)}$$

Dividing (xiv) by (xiii) we get

$$\frac{M_T}{M_t} = \frac{d_1^3}{d_2^3}.$$

By substituting for known quantities in the above expression, we get the mean coefficient, $\alpha$, required. Let the magnet cool to its original temperature, and note that it has become weaker.

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## D. THE VIBRATION METHOD.

Just as a simple pendulum, when slightly displaced from its vertical position of rest, will vibrate isochronously under the force of gravity, so a freely suspended magnet vibrates isochronously when slightly displaced from its position of rest in a uniform field of force. It can be shown that the intensities of two uniform fields are proportional to the squares of the numbers of vibrations performed in the same time by a magnet, placed successively in the two fields. Thus if $F$, $F'$, are the intensities of two uniform fields in which the same magnet makes respectively $N$, $N'$ vibrations in the same time, then

$$\frac{F}{F'} = \frac{N^2}{N'^2}.$$ (p. 36)

The **Vibration Box** is an oblong box with moveable plane glass sides. Through the middle of the cover is a hole in which fits a vertical glass tube. The magnet is suspended inside the box by a brass stirrup, supported by a torsionless thread passing up the glass tube, and attached to a moveable cap closing the top of the tube. The bottom of the inside of the box consists of a plane mirror with a line, cut by a diamond, bisecting it along its length. Before using the instrument we have to adjust it so that this line lies in the magnetic meridian, i.e. so that the axis of the magnet, when at rest under the earth's force, lies over this line.

When the magnet is vibrating we can, by looking down through a slit in the cover, observe when it crosses the line

cut on the mirror. For greater accuracy a triangular piece of paper should be attached to the two ends of the magnet.

Instead of the vibration box, we might support the magnet by a torsionless thread from a wooden clamp, or better still, to prevent draughts of air affecting its motion, inside a deflagrating jar. The jar can be easily made by taking off the bottom of a Winchester quart bottle as follows. Tie round the bottle, at a convenient distance from the bottom, a piece of worsted which has been soaked in methylated spirits. Cut off the ends of the worsted, and set fire to it. Holding the bottle horizontally, keep turning it round, and before the flame has gone out, plunge it bottom downwards into cold water. A chalk line should be drawn on the table in the direction of the magnetic meridian, and the magnet adjusted so that its axis lies above this line when at rest under the earth's force.

**13. To compare the intensities of the magnetic fields in two different places.**

*Apparatus.* A Vibration Box or a Magnet suspended in a deflagrating Jar: a Stop-watch.

*Experiment.* Adjust the magnet properly. Displace it slightly from the magnetic meridian, and note the time taken by it to make ten complete vibrations[15]. Take the time of another ten vibrations. If the observed times do not differ by more than three-fifths of a second, take the average (see Note 8), and calculate the number of vibrations, $N$, it would make in a minute.

Transfer the magnet to another part of the room or to another room, and find as above the number of vibrations, $N_2$, it would make in a minute in its new position. If the intensities of the fields in the two places are $H$, $H'$, respectively, then

$$\frac{H}{H'} = \frac{N^2}{N'^2}.$$

[15] The time of a complete vibration is the time that elapses between the moment at which an end of the magnet passes a given point and that at which it again passes the same point *in the same direction*. Least error is made if we begin reckoning when the end is moving most quickly, i.e. when it is passing acrcss the magnetic meridian.

The magnetic fields thus compared are not in general due to the earth alone, but are the resultant fields due to the earth's magnetism and the magnetism induced by the earth in any fixed pieces of iron in the neighbourhood of the magnet.

**14. To compare the field intensities due to two magnets at a given point by the vibration method, and to compare the pole-strengths of the magnets.**

*Apparatus.* Two Bar Magnets: a Magnetoscope: a Stop-watch: a Metre Rule.

*Experiment.* Draw a chalk line on the table to indicate the direction of the magnetic meridian. At a given point place the magnetoscope so that the needle, when at rest under the earth's forces, lies along the chalk line. Find the time in which the needle makes fifty vibrations under the earth's horizontal force, $H$, twice, and if they do not differ by more than three-fifths of a second take the average and calculate the number of vibrations, $N$, it would make in a minute. Then

$$H \propto N^2.$$

To the north of the magnetoscope place the stronger of the two magnets, with its axis lying along the chalk line and its N. pole pointing southwards, at such a distance off that the needle does not turn round. Note the distance, $d$, between its mid-point and the magnetoscope. The resultant force of the magnet repels the north pole of the needle, and its field, $h_1$, is opposed to that of the earth, hence the field in which the needle swings is $H - h_1$ (see Note 7). Determine as before the number of vibrations, $n_1$, it would make in a minute. Then

$$H - h_1 \propto n_1^2.$$

Replace the magnet by the other one in a similar position, so that the distance between its mid-point and the needle is exactly the same as in the former case, and as before find the number of vibrations, $n_2$, made by the needle in a minute. If $h_2$ is the field due to the magnet, the resultant field is $H - h_2$.

Then $$H-h_2 \propto n_2^2,$$

$$\therefore \quad \frac{h_1}{h_2}=\frac{N^2-n_1^2}{N^2-n_2^2}.$$

Now repeat the above, placing the magnets in the same position as before, but with their S. poles pointing southwards. In this case their fields are in the same direction as that of the earth, and the resultant fields are

$$H+h_1, \; H+h_2.$$

If $n'_1$, $h'_2$, are the numbers of vibrations made by the needle in a minute in these fields respectively,

$$\frac{h_1}{h_2}=\frac{n'_1-N^2}{n'_2-N^2},$$

which ought to give the same ratio as before.

We can compare the pole-strengths of the two magnets by substituting known quantities in Equation (ii), and putting $m'=1$.

The time, $t$, in seconds of a complete vibration of a magnet, depends upon

(i) the moment, $M$, of the magnet;

(ii) the 'moment of inertia,' $I$, of the magnet, which depends on its mass, shape, and dimensions;

(iii) the intensity of the field, $H$, in which it vibrates, and is given by

$$t=2\pi\sqrt{\frac{I}{MH}}. \qquad \text{(xv)}$$

Hence $MH \propto \frac{1}{t^2}$ or $\propto n^2$, if $n$ is the number of vibrations made in a second, or if $N$, $N'$, are the numbers of vibrations, made by the same magnet in the same time, in two fields whose intensities are $F$, $F'$, then

$$\frac{F}{F'}=\frac{N^2}{N'^2}.$$

The moment of inertia, relative to the axis of suspension, is

($a$) in the case of a cylindrical magnet of radius $r$, and length $l$,

$$I = P\left(\frac{l^2}{12} + \frac{r^2}{4}\right);$$

(*b*) in the case of a bar magnet of rectangular section of length $l$, and horizontal breadth, $b$,

$$I = P\left(\frac{b^2 + l^2}{12}\right),$$

where $P$ is the mass of the magnet in grams.

We can from Equation (xv) compare the moments of $M_1$, $M_2$, two magnets, by finding by measurement and weighing their moments of inertia $I_1$, $I_2$, and the times, $t_1$, $t_2$, taken by each to make the same number of vibrations, or the numbers, $n_1$, $n_2$, of vibrations made in the same time for

$$\frac{M_1}{M_2} = \frac{I_1 t_2^2}{I_2 t_1^2} = \frac{I_1 n_1^2}{I_2 n_2^2}.$$

If the magnets are of the same shape, weight, and dimensions,

$$I_1 = I_2, \quad \text{and} \quad \frac{M_1}{M_2} = \frac{n_1^2}{n_2^2}.$$

***15. To determine the moment of a magnet, and the horizontal component of the earth's magnetic field.**

*Apparatus.* A Magnet: Vibration Box: Magnetometer: a Balance and Box of Masses: a Stop-watch: a Pair of Callipers.

*Experiment.* (i) To determine the product $MH$.

Adjust the vibration box properly. Find the time taken for the magnet to make twenty complete vibrations. Repeat this twice more, and if the times do not differ by more than two-fifths of a second, take the average, and deduce the time, $t$, of one vibration. If $M$ is the moment of the magnet, $I$ its moment of inertia, $H$ the horizontal component of the earth's force, we get from Equation (xv)

$$MH = \frac{4\pi^2 I}{t^2}.$$

Deduce the value of $I$ according to the shape of the magnet, measuring the lengths by the callipers, the mass $P$ by the balance.

Substitute for known quantities and deduce the numerical value of $MH$. Let it be $a$.

(ii) To determine the quotient $\frac{M}{H}$.

Take the magnet out of the vibration box, and place it on the W. arm of the magnetoscope, so that the deflexion of the needle is about 45°. Note the distance, $d$, of its mid-point from the centre. Read both the ends of the pointer. Transfer the magnet to the E. arm, reversing the poles, at exactly the same distance from the centre as before. Read the ends of the pointer. Take the average of the four angles as the angle of deflexion, $\alpha$, corresponding to the distance, $d$. Knowing the length, $l$, of the magnet from the previous experiment, by substitution for known quantities in Equation (vi) we get the value of $\frac{M}{H}$. Let $b$ be the numerical value of this quotient.

$$MH \div \frac{M}{H} = H^2 = \frac{a}{b},$$

$$\therefore \quad H = \sqrt{\frac{a}{b}}.$$

$$MH \times \frac{M}{H} = M^2 = ab,$$

$$\therefore \quad M = \sqrt{ab}.$$

Assuming the poles of the magnet to be at the ends, we can get the strength of the pole by dividing $M$ by the length of the magnet.

# II. ELECTRICITY

In addition to the apparatus and material, usually at hand in a Chemical Laboratory, the following will be required. Those in italics are not indispensable.

Different kinds of battery cells.
Two contact keys.
Plug key.
Commutator (Fig. 16).
Voltameter (Fig. 3).
Mixed-gas voltameter (Fig. 6).
Two electrolytic cells (Fig. 5).
*Differential electrolytic cell* (Fig. 15).
Copper sulphate rheostat (Fig. 14).
High and low-resistance galvanoscope.
Seven-coiled tangent galvanometer.
Reflecting galvanometer.
Box of resistance coils.
Separate resistance coils, about 50, 80, 100 ohms.
Metre bridge (Fig. 11).
*Post Office bridge.*
Potentiometer (p. 98).
Calorimeter (p. 104).
Covered and uncovered copper and German silver wire of B.W.G. 22, 25, 29.
Clamps.
Metre rule.

# PRACTICAL WORK IN ELECTRICITY

## A. Battery Cells and Simple Effects of an Electric Current.

In order to understand the meaning of '*difference of electrical level or potential*,' a term in constant use, let us first get a clear idea of the somewhat analogous term, 'difference of water level.' If two cisterns of water are joined by a pipe, already full of water, the level is said to be the same if there is no flow from one to the other. If there is a flow, the water in the cistern from which the flow proceeds is said to be at the higher level. The flow will continue until the water is at the same level in the two cisterns. If the original difference of level were kept constant by causing water to flow into one and out of the other at the same rate, the 'strength of the current' may be measured by the quantity of water passing in one second through any given section of the pipe perpendicular to its length. Assuming the water to be incompressible, it is evident that however irregular the section of the pipe may be at different points in its length, the same quantity will be passing through any section, greater or smaller, at a given moment. The strength of the current does not depend upon the size of the cisterns, or upon the quantities of water they contain, but only upon the difference of level. The level of a water surface

has no meaning except as referred to an arbitrarily chosen level—usually that of the sea, which may be called zero-level, the capacity of the sea being so great that a flow of water to or from it does not sensibly alter its level. If we connect the sea by a pipe, filled with water, to the bottom of a cistern containing water, then, if there is no flow between the two, the water in the cistern is at zero-level: if there is a flow, it is at a positive or negative level according as the flow is to or from the sea respectively. In an analogous way we may define electrical level or potential. If two bodies, charged with electricity, are joined by a metallic wire, the two bodies are said to be at the same potential if there is no flow of electricity from one to the other. If there is a flow, the body from which the flow proceeds is said to be at the higher potential. The flow will continue until both bodies are at the same potential. If there is, as in the case of an electric battery, a source of energy tending continually to keep up the original difference of potential, the strength of the current may be measured by the quantity of electricity passing in one second through any given section of the wire. However irregular the section of the wire may be, the same quantity of electricity will be passing through any section, greater or smaller, at a given moment. The strength of the current does not depend upon the size of the charged bodies, or upon the quantities of electricity they contain, but only upon their difference of potential. The potential of a charged body is for practical purposes referred to that of the earth, which is said to be at zero-potential, the capacity of the earth being so great that a flow of electricity to or from it does not sensibly alter its potential. If we connect the earth by a metallic wire to a body, then, if there is no flow of electricity between the two, the body is at zero-potential; if there is a flow, it is at a positive or negative potential according as the flow is to or from the earth respectively.

In comparing the flow of electricity to that of water, we must carefully guard ourselves against the idea that electricity is a material substance. Nothing flows through the wire and it

is not the wire that is the immediate cause of electrical phenomena. They are due to the strained condition of the ether surrounding it, but since most of the effects are of the nature of 'vectors,' i.e. have a relation to direction such that when we change the direction of the current, the effects are reversed, we may use the term 'electric current,' being always on our guard against the idea of material motion.

**Volta's Cell.** If we dip a sheet of commercial zinc in dilute sulphuric acid the zinc dissolves, forming zinc sulphate, and the hydrogen is set free from the acid. Perfectly pure zinc is not under ordinary conditions attacked by the acid, and we can prevent a sheet of commercial zinc from being attacked by it by 'amalgamation.' This consists in dipping the zinc into sulphuric acid in order to clean it and then rubbing a little mercury over it to form an amalgam with the zinc, thereby producing a smooth surface. As little mercury as possible should be used, as the zinc becomes brittle and falls to pieces if the mercury penetrates too far into the interior. Three grams of mercury are sufficient to amalgamate 100 sq. cm. of zinc. The zinc should be well washed afterwards.

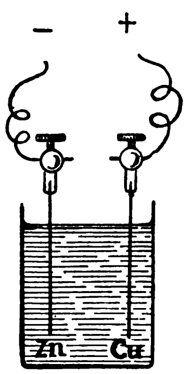

Fig. 1.

Arrange a sheet of copper and of amalgamated zinc vertically without touching each other in a beaker of dilute sulphuric acid. Solder a length of copper wire on to the projecting edges of the plates, or pass the wires through brass terminals previously soldered to the edges. This arrangement constitutes a simple Volta's cell (Fig. 1). Before the free ends of the wires are joined (i.e. when the cell is on *open circuit*) nothing apparently happens. On joining the wires (i.e. when the cell is on *closed circuit*) we notice—

i. *Inside the cell:*

(*a*) Hydrogen gas is given off at the surface of the copper plate.

(*b*) Zinc sulphate is formed in the cell, which we can test by chemical means[1].

(*c*) The liquid becomes warm, which we can test by a thermometer.

ii. *Outside the cell:*

The copper wire has acquired new properties. Lay the wire along the magnetic meridian above or below a freely suspended magnetic needle. The needle will be deflected out of the meridian. These newly acquired properties, the rest of which will be considered later, are said to be due to an electric current flowing through the wire.

On open circuit the free ends of the copper wire may be shown by experiment to be at different potentials, the end of the wire connected to the copper plate (called the + pole) being at a higher potential than the end of the wire connected to the zinc plate (called the — pole), therefore on joining them a flow of electricity takes place. The chemical action inside the cell tends to keep up this difference of potential, hence, as long as the chemical action continues, an electric current will circulate round the complete circuit. We can make a cell of any two different metals immersed in a liquid which acts chemically upon one of them. Thus iron may replace the zinc, or hydrochloric acid a solution of common salt, or water can replace the sulphuric acid.

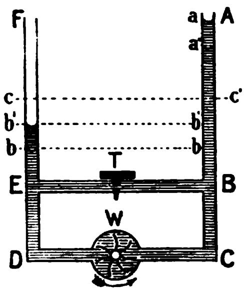


Fig. 2.

We may illustrate the action of a cell by the hydrostatic model of Fig. 2. *AC*, *FD* are two vertical pipes joined by two horizontal pipes, *BE*, *CD*. In *BE* is a tap, *T*, by which we can open or close the passage through it. In *CD* is a large bulb, in which a fan-wheel, *W*, can be made to rotate round an

[1] The chemical action in the Volta's cell is given by
$$Zn + H_2SO_4 = ZnSO_4 + H_2.$$

axis perpendicular to the plane of the paper. Suppose the whole system of pipes at first to be filled with water up to the level $cc'$. Turn the tap $T$ so as to close the passage through $BE$. If by some means a rapid rotation is given to $W$ in the direction of the arrow-head, water will be forced up $AC$ until it reaches a level, $a$, the level in $FD$ sinking to $b$. This difference of level may be compared to the difference of potential between the ends of the wires of a cell on open circuit. On turning the tap, $T$, so as to open the passage through $BE$, a continuous current of water will flow round $BEDCE$, as long as $W$ rotates, and at the same time the level of water in $AC$ drops to $a'$, that in $FD$ rises to $b'$. The difference of level now forcing the water through $BE$ is less than that before the tap was turned, as a part of the original difference of level is used to force the stream through $DC$. The turning of the tap corresponds to the joining the terminals of the zinc and copper plates by a wire, the current of water to the current of electricity passing round the closed circuit, and the energy required to rotate $W$ to the chemical energy developed in the cell. The original difference of level before the tap $T$ was turned corresponds to the E.M.F. of the cell on open circuit, the smaller difference of level, when the water is circulating, to the smaller difference of potential at the terminals of the cell on closed circuit, which we shall call the *terminal potential difference*, or P.D., the difference between the two being employed in sending the current through the cell itself.

We can obtain a greater E.M.F. by joining up two or more cells 'in series,' i.e. by connecting the copper plate of one cell with the zinc plate of the next. If we join $n$ cells thus in series, the E.M.F. of the battery is $n$ times as great as that due to one cell alone.

If we allowed the current from a Volta's cell to deflect a compass needle from the magnetic meridian we should find the original deflexion decrease after a time, the needle gradually returning to the meridian, showing that the current from a Volta's cell is not constant, but decreases with the time. This decrease is due (i) to the fact that the sulphuric acid is

being continually transformed into zinc sulphate, which offers a greater obstruction to the passage of the current, and (ii) to the deposition of hydrogen on the copper plate, which is called the 'polarization of the copper plate.' This acts in two ways—(*a*) the layer of hydrogen offers an obstruction to the passage of the current, and (*b*) the contact of the gas with the copper plate creates a difference of potential called the 'back E.M.F.', tending to send a current in the opposite direction. The polarization of the copper plate is the more serious defect of the cell, and numerous cells have been invented to prevent it or to lessen it.

The following are the cells in more frequent use, in all of which polarization is prevented by causing the hydrogen, when set free, to enter into chemical combination with other substances. In all these cells zinc is one of the metals used.

**1. Single fluid cells.**

(*a*) *Leclanché.* The depolarizer is black manganese dioxide ($MnO_2$) packed with bits of carbon round a carbon rod in a porous pot of unglazed earthenware. The pot is closed at the top with pitch and a hole is left so that a little water may be poured in to help the commencement of the action. Contact with the carbon rod is made by means of a lead cap cast on it, bearing a brass terminal. The porous pot rests in a vessel nearly full of a strong solution of ammonium chloride ($NH_4Cl$), in which dips a rod of zinc. The chemical action that occurs on closed circuit is given by

$$Zn + 2\,NH_4Cl = 2\,NH_3 + ZnCl_2 + 2\,H$$
$$2\,H + 2\,MnO_2 = Mn_2O_3 + 2\,H_2O.$$

The E.M.F. falls rapidly on closed circuit, but quickly regains its former strength on open circuit; hence this cell is used for electric bell work.

($\beta$) *Chromic Acid.* The depolarizer is chromic oxide ($CrO_3$) dissolved in water, forming chromic acid. The cell is usually in the shape of a wide-necked decanter. The solution, which should fill it about three parts full, is made by dissolving

chromic oxide in water and adding 3½ times its mass of strong sulphuric acid. To a terminal on the ebonite cover are attached two plates of gas carbon, which dip into the solution. Between them slides a sheet of amalgamated zinc attached to a brass rod passing through a collar fixed to the cover. The brass rod can be fixed at any height by a brass screw connected with another terminal. When not in use the zinc must be raised out of the liquid. The chemical action that occurs on closed circuit is given by

$$3\,Zn + 6\,H_2SO_4 + 2\,CrO_3 = 3\,ZnSO_4 + Cr_2\,(SO_4)_3 + 6\,H_2O.$$

Instead of the above solution, we may use one made by dissolving 12 grs. of potassium bichromate ($K_2Cr_2O_2$) in 100 cc. of water and adding 25 cc. of strong sulphuric acid. Crystals of chrome alum ($K_2SO_4$, $Cr_2(SO_4)_3$) are deposited on closed circuit. Sodium bichromate, which is cheaper and more soluble and forms no double sulphate, may be used in place of potassium bichromate.

When the solution turns blue more chromic acid or potassium bichromate must be added, and, if the cell is not in good working order when the solution is still of an orange colour, add some more sulphuric acid.

This cell has a low resistance and is suitable for general purposes. The E.M.F. runs down on closed circuit when sending a strong current, but nearly regains its original value on open circuit.

**2. Double fluid cells.**

($a$) ($\beta$) *Grove's* and *Bunsen's*. The depolarizer is strong nitric acid contained in a porous pot of unglazed earthenware, in which dips a sheet of platinum in the Grove's, or a rod of gas carbon in the Bunsen's cell. The porous pot is placed in an outer jar nearly full of dilute sulphuric acid containing a sheet of amalgamated zinc. The chemical action that occurs on closed circuit may be represented by

$$Zn + H_2SO_4 = ZnSO_4 + 2\,H$$
$$2\,H + 2\,HNO_3 = 2\,NO_2 + H_2O.$$

The cells have a small resistance and their E.M.F. is high, hence they are adapted for general use. When in use the cells should be placed in a draught-cupboard, as nitrous fumes arise from the nitric acid.

(γ) *Daniell.* An amalgamated rod of zinc dips into dilute sulphuric acid contained in a porous pot, which is placed in a saturated solution of copper sulphate, nearly filling an outer copper pot, to the edge of which a terminal is attached. The chemical action that occurs on enclosed circuit is given by

$$Zn + H_4SO_4 = ZnSO_4 + 2\,H$$
$$2\,H + CuSO_4 = H_2SO_4 + Cu.$$

The copper set free is deposited on the inside of the copper pot. The solution of copper sulphate must be kept saturated by contact with crystals of the same placed on a perforated ledge immersed in the solution. The cell has a comparatively large resistance, but the E.M.F. is fairly constant, hence it is used in cases where a constant, but not necessarily strong, current is required—e. g. in electro-plating, &c.

To get a constant E.M.F. a solution of zinc sulphate, of the same density as the copper sulphate, should be used instead of the sulphuric acid, and the cell should be 'short circuited' for five or ten minutes before use.

N.B. Before using a cell it is necessary to amalgamate the zincs to prevent them being dissolved in the sulphuric acid on open circuit, i.e. to prevent 'local action,' and the terminals and free ends of all connecting wires should be scraped bright. In the case of double fluid cells, when not in use, the zincs should be taken out and rinsed, the liquids should be poured into stock bottles and the porous pots kept under water. We shall represent a cell in diagram by ▮|, the thick short line being the zinc plate, the long thin one the copper or carbon plate.

The E.M.F.'s of different cells have different values, which we can measure in terms of a suitable unit. The practical unit of E.M.F. is called a *volt*, which may be taken to be the difference of potentials on open circuit of a simple cell, made of

a sheet of copper, and one of amalgamated zinc, dipping into distilled water. The values in volts of the E.M.F.'s of different cells are given in Appendix B, 2 The E.M.F. depends only on the materials of which the cell is made, and not upon its size. Thus the E.M.F. of a large and a small Daniell's cell is the same provided the solutions are of the same strength.

The properties of an electric current can now be satisfactorily studied by using two or three chromic acid cells joined up in series.

1. *Heating Effect.* The energy of an electric current has its origin in the resultant disengagement of heat produced in the cell by the chemical action. If no useful work is done by the current, such as in deflecting a magnetic needle from the meridian, or in working a machine, all the energy of the current is again transformed into heat, which is developed in different parts of the circuit, the quantities of heat appearing in the different parts being proportional to their resistances[2]. On joining the terminals of the battery by a long, fine platinum or German silver wire, most of the heat appears in the wire in consequence of its relatively great resistance, and a less quantity appears in the cell. Take the temperature of the liquid in a cell by a thermometer. On substituting a short thick copper wire, which has a low resistance, the wire becomes warm, but most of the heat appears now inside the cells, raising the temperature of the liquid higher than it was before.

2. *Chemical Effects.* Liquids that allow a current to pass through them are called 'electrolytes.' They are at the same time always decomposed by the current; in fact, the essential condition that they should transmit a current is that they are able to be decomposed by it[3].

(*a*) To show the decomposition of water, we can use a 'voltameter' of the following simple construction (Fig. 3).

[2] For the definition of the resistance see p. 58.
[3] Water, solutions of metallic salts, acids, are instances of electrolytes, oil and turpentine of non-conductors. Mercury acts as a metallic conductor.

Crack off the bottom of a bottle of 8 to 10 cm. in diameter [4], *B*, and close the neck with a cork, through which two holes have been bored by a knitting-needle. Weld two platinum wires to two strips of platinum foil 2 cm. long and 1 cm. wide. Pass the wires through the cork until the strips are in the middle of the bottle. Warm the bottle all round and pour into it some melted paraffin wax until the strips only are exposed, which should be arranged vertically. Pass the wires through a hole in the base-board, *A*, into which

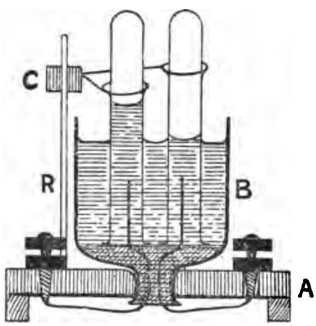

Fig. 3.

the neck of the bottle is firmly fixed, and solder them to two terminals previously screwed into the board. A cube of cork, *C*, sliding on a wooden penholder, *R*, serves as a support for two wire rings, in which rest two equal test-tubes inverted over the platinum strips. Nearly fill the funnel with acidified [5] water (1 part of sulphuric acid to 10 parts of water). Fill the test-tubes also with the liquid, and invert them over the platinum strips. On joining the terminals of the voltameter to the battery, the water is decomposed, the volume of the hydrogen, which is given off at the strip connected with the zinc end of the battery, being nearly twice as great as that of the oxygen [6]. The gases may be tested in the usual way.

(*b*) To show the decomposition of a metallic salt, empty the voltameter and test-tubes and replace the acid solution by a solution of copper sulphate, inverting the test-tubes filled with the same over the strips. On passing a current the copper

[4] See on p. 34, *Magnetism*.

[5] Pure water has a very high resistance. In order that the current may be sufficiently strong to effect the decomposition quickly, the acid is added to lessen the resistance. Acidulated water is of maximum conductivity when its density is 1·25.

[6] Oxygen is more than twice as soluble as hydrogen in water. Some ozone is also formed. For both reasons the oxygen will be somewhat less than half the volume of hydrogen given off.

sulphate is decomposed, bubbles of oxygen gas rise from the strip connected with the carbon end and collect in the test-tube, and copper is deposited on the strip connected with the zinc end of the battery. The chemical action occurs in two stages:

Primary decomposition $CuSO_4 = Cu + SO_4$,
Secondary decomposition $2\ SO_4 + 2\ H_2O = 2\ H_2SO_4 + O_2$.

*Direction of the Current.* The metallic radicle travels with the current and therefore is deposited on the strip at which the current leaves the liquid, which is the one connected with the zinc end of the battery. Hence, supposing the current starts from the metal (zinc) dissolved in the cell, it passes inside the cell from the zinc (+plate) to the copper or carbon (−plate), and outside the cell from the terminal (+pole) connected to the copper or carbon, to that (−pole) connected to the zinc. A cell is represented, as in Fig. 7, by a thick and a thin line, the thick line being used for the zinc plate and the thin for the copper, platinum, or carbon plate.

3. *Magnetic Effects.* We have seen above that an electric current deflects a compass needle from the magnetic meridian; hence produces a magnetic field in its neighbourhood. To plot the lines of force due to a rectilinear current, pass a long thick copper wire through the middle of a piece of cardboard. Fix the wire vertically in a wooden clamp and support the cardboard so that its plane is horizontal. Attach the ends of the wire to the terminals of a battery of five or six chromic acid cells, and plot the lines of force in the plane of the cardboard as in Experiment 2 of *Magnetism* (p. 7). We shall find they are concentric circles around the wire. Their direction, i.e. the direction along which a compass needle comes to rest, is given by either of the following rules:—

(*a*) Extend the fingers and thumb of the right hand, placing the palm facing the needle, with the fingers pointing in the direction of the flow of the current, so that the wire is between the hand and the needle. Then the north pole is deflected in the direction in which the thumb is pointing.

(*b*) Imagine a right-handed corkscrew to be turned so that its point travels in the direction of the current, then the direction of the lines of force is that in which the ends of the handle rotate.

The student should become familiar with these rules by observing the deflexion of a needle when a wire is placed above or below it, both before and after altering the direction of the current.

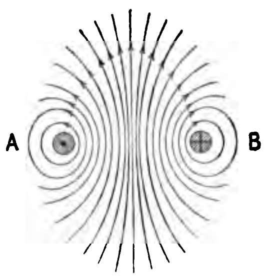


Fig. 4.

If we bend the wire into a circle the concentric lines of force round each element trend in the same direction. Fig. 4 is a diagram showing the line of force in a plane through the centre perpendicular to the plane of the circle, in which the current is supposed to come up at *A* and to go down through the plane at *B*.

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## B. Chemical Effects of a Current.

*Faraday's Laws.* Faraday studied the laws of the chemical action of the electric current, which may be stated as follows:—

1. The same strength of current passes round a simple circuit.

2. The amount of chemical action varies directly as the time during which the current passes.

3. The amount of chemical action varies directly as the strength of the current.

4. If the same current is passed through solutions of different metallic salts, the masses of metals deposited in the same time are proportional to their chemical equivalents[7].

[7] The chemical equivalent of a metal is that mass of it which can replace

The vessel in which the electrolyte is contained is called the 'electrolytic cell,' and may be made as follows. *C* is a glass vessel (Fig. 5) such as is used in a Grove's cell, and *W*, a square wood framework with the length of its sides slightly larger than those of the vessel. Through two opposite sides of the frame pass two thick brass wires, projecting about 2 cm. To them are fixed two terminals, to which the wires from the battery are to be attached. Two metal plates, *A*, *K*, called 'electrodes,' have an edge turned over, so that they may rest on the brass wires and dip into the electrolyte. Connexion with the battery being made as in the figure, the current enters the solution by the plate *A*, the 'anode,' and leaves it by the plate *K*, the 'kathode.' (i) When the electrolyte is a solution of copper sulphate, the electrodes are of copper. No oxygen comes off the anode, as is the case when the electrodes are of platinum (p. 51), but copper is dissolved off the anode and is deposited on the kathode. Hence, the kathode should be a thin sheet of copper to lessen the error in weighing the mass of copper deposited on it, and the anode should be made of a thicker sheet. (ii) When the electrolyte is a solution of silver nitrate, a fairly thick sheet of pure silver should be used for the anode, and a thin copper sheet, previously covered with a deposit of silver by simple immersion in silver nitrate, for the kathode. It is better to have two anodes, one on each side of the kathode, resting on two wires, soldered together on the outside and provided with a terminal, since in this case deposition takes place on both sides of the kathode.

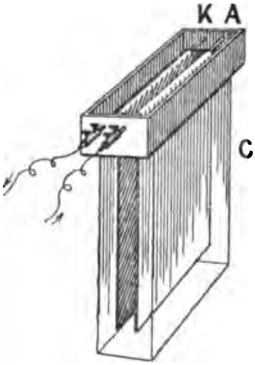


Fig. 5.

From Law 3 it is evident we have a means of comparing current strengths by the chemical action each produces in the

1 gram of hydrogen in an acid. It is given by the number obtained by dividing the atomic weight of the metal by its valency.

same time. The practical unit[8] in which currents are measured is called **one ampère,** and is that current which in one second will deposit ·001118 grains of silver from a solution of silver nitrate. (*Board of Trade Report*, 1891.)

The **electro-chemical equivalent,** $\epsilon$, of a metal is the mass which is deposited from a solution of one of its salts in one second by one ampère. The electro-chemical equivalent of silver being known we can, by Law 4 above, find those of any other element by simple proportion.

Thus, for hydrogen:

$$\epsilon_H : \cdot 001118 :: 1 : 108 \quad \text{or} \quad \epsilon_H = \cdot 00001035 \text{ grams.}$$

To get the vàlues of other elements multiply the electro-chemical equivalent for hydrogen by their chemical equivalents. Thus:

$$\epsilon_{Cu} = \cdot 0000104 \times 31 \cdot 5 = \cdot 000326 \text{ grs. for cupric salts;}$$

$$\epsilon_O = \cdot 0000104 \times 8 \quad = \cdot 0000832 \text{ grs. for oxygen.}$$

It is evident that we can determine the strength of any current in ampères by passing it through a metallic salt and finding the mass of the metal, whose electro-chemical equivalent is known, which is deposited by the current in a given time.

### 1. To prove that the chemical action of a current is indirectly proportional to the time during which the current passes.

*Apparatus.* A Mixed-gas Voltameter: a graduated Burette fitted with a piece of india-rubber tubing and a clip: a Glass Dish: a Watch: four Daniell's Cells in series.

[The mixed-gas voltameter (Fig. 6) may be readily made by fitting a wide-mouthed bottle with a three-hole bung. Into the closed ends of two glass tubes, *T*, *T'*, fuse pieces of platinum wire so that they project about ·5 cm. within the tubes. To each of the exposed ends of the wires weld a platinum strip, *P*, and fit the glass tubes into two holes in the bung. Into the third hole fit a rather narrow delivery tube, with its free end bent hori-

[8] The absolute electro-magnetic unit of current is explained in Appendix A, 2.

zontally, dipping into the glass dish, *D*. Connexion with the battery is made by dipping the leads into mercury poured into the two tubes.]

*Experiment.* Nearly fill the voltameter with water and add to it some phosphorus pentoxide, obtained by burning phosphorus in air under a dry bell-jar. The oxide dissolves in the water and forms phosphoric acid, which prevents the formation of ozone. Pass a current for two or three minutes through the water[9] so as to saturate it with dissolved oxygen. While this is going on fill the burette with water and invert it in water contained in the dish. Place the end of the delivery tube under the burette and note the times at which the level of the water in the burette reaches every successive 20 c.c., i. e. in which equal volumes[10] of mixed gases are set free. They will be found to be very nearly equal, proving that the chemical action is directly proportional to the times during which the current passes.

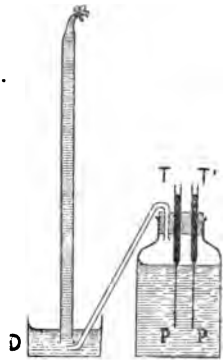

Fig. 6.

***2. To prove that the masses of metals deposited from solutions of their salts by the same current in the same time are directly proportional to their chemical equivalents.**

*Apparatus.* Solutions of Copper Sulphate (20 grs. in 100 c.c. of water, and add 5 grs. of strong sulphuric acid) and of Silver Nitrate (10 % solution), contained in two electrolytic cells with their proper electrodes, as explained above: a Plug Key: a Balance: a Box of Masses: one or two Battery Cells.

*Experiment.* See that the contacts between the electrodes and the brass wires are bright. Polish the electrodes with sand

[9] Being very careful no light is near, as the mixed gases are explosive.
[10] We neglect the varying pressures under which the gases are evolved.

till they are uniformly bright[11]. The portion to be immersed in the liquid is on no account to be touched by the fingers. Arrange the cells in series with the plug key and the battery cells, placing the thinner electrode in each cell on the brass wire at which the current leaves the cell. Close the circuit by putting in the plug key and let the current pass for a short time, then take out the kathodes and see whether the deposits are firm, uniform, and not granular[12]. When the current is arranged of the proper strength break the circuit by taking out the plug key, take the kathodes out, wash them with distilled water, dip them into alcohol, and dry them over a Bunsen's flame. After weighing them carefully, replace them in their cells. Close the circuit at a given moment and let the current pass, say for half an hour. Break the circuit and take the kathodes out, wash, dry, and weigh them as before. The increase of mass in each will give the mass of copper and silver deposited respectively, and the ratio of these masses will be found to be in the proportion of the chemical equivalents of the metals, i.e. as 31·5 : 108.

N.B. This law not only holds for metals deposited in electrolytic cells, but also for the chemical action that goes on in each cell of the battery. Thus, in the case of a battery sending the same current through solutions of copper sulphate and silver nitrate and a water voltameter, the amount of zinc dissolved in each battery cell is chemically equivalent to the amount of copper or silver deposited, and of hydrogen and oxygen set free in the voltameter. Thus, while ·325 grs. of zinc are dissolved in each battery cell, 1·08 grs. of silver and ·315 grs. of copper are deposited, and ·01 gr. of hydrogen and ·08 gr. of oxygen are evolved, or ·09 gr. of water is decomposed.

[11] The copper plates may be cleaned by being dipped into a mixture of strong nitric and sulphuric acids, to which ¼th of the total volume of water is added, and then washed with water.

[12] The current should not exceed the proper current density suitable to the given areas of the electrodes. The current may be varied within much wider limits for the copper (50 to 60 sq. cm. to one ampère) than for the silver. The current should be arranged so that the silver deposited is of a white ivory colour. If darker the current is too strong.

## C. WHEATSTONE'S BRIDGE AND ITS USE.

**Galvanoscopes.** To detect a current, or to find whether one current is greater or less than another, we can employ any one of its effects. The instruments in more common use for this purpose depend on the deflexion of a magnetic needle from the magnetic meridian, and are called *Galvanoscopes*[13]. They consist essentially of a coil of wire generally wound in a rectangular form surrounding a magnetic needle. To increase the angle of deflexion for a given current, i.e. to increase the sensitiveness of the instrument—

(*a*) The effect of the current, tending to deflect the needle from the meridian, is increased by winding many turns of wire round and as close as possible to the needle.

(*b*) The effect of the earth's force, tending to bring the needle back to the meridian, is decreased by using an 'astatic' combination, i.e. a pair of needles of nearly equal strength, one of which is in the middle of the coil, the other being above a graduated circle fixed on the top of the coil, both needles being rigidly connected with their poles reversed, the N. pole of one being above the S. pole of the other.

For weak currents a long coil or high-resistance galvanoscope is used, in which the coil is made of a large number of turns. The effect of the large number of turns on the deflexion outweighs the disadvantage of the wire being necessarily thin and therefore of high resistance. For strong currents a short coil or low-resistance galvanoscope is used, having but few turns of thick wire. It is an advantage to have an instrument in which the long and short coils are interchangeable. Galvanoscopes do not measure or compare current strengths, as the latter bear no simple relation to the deflexions produced by them.

**Ohm's Law.** It is found by experiment that if a continuous current is flowing through a wire there exists a difference of potential between the ends of the wire, to which the current

[13] A galvanoscope is indicated in diagrammatic form as in Fig. 7 *G*.

through it is due, and if the wire be homogeneous, and of uniform section, the difference of potential between any two points is directly proportional to the length of the wire between the points. If the difference of potential is kept constant, and the length of the wire is altered, the current strength is found to vary inversely as the length. Again, if we alter the diameter of the wire, i.e. its sectional area, keeping the length and material constant, the current strength varies directly as the sectional area. Again, if we use wires of different materials, but of the same length and sectional area, the current strength varies, being, for instance, less through a German silver than through a copper wire. This property of a wire, in virtue of which the current, due to a constant difference of potential at its ends, varies when the length material or sectional area is altered, is called the **resistance** of the wire. Its resistance, $r$, is therefore proportional directly to its length, $l$, and inversely to its sectional area, $a$,

$$\therefore \quad r \propto \frac{l}{a},$$

$$\text{or} \quad r = k\frac{l}{a},[14] \qquad \text{(i)}$$

where $k$, a constant depending on the material only, is equal the resistance of 1 c.c. of the material, and is called its **specific resistance.** The reciprocal $\frac{1}{k}$ is called its **specific conductivity.** If $e$ is the difference of potential between the ends of a wire of resistance $r$, and $C$ the current strength through it, then, from what has been said above,

$$C \propto \frac{e}{r},$$

$$\text{or} \quad r \propto \frac{e}{C},$$

$$\therefore \quad r = K\frac{e}{C},$$

[14] This also applies to the resistance of an electrolyte where $l$ is the distance between the electrodes and $a$ the area immersed.

where $K$ is some constant number depending on the units employed to express the different quantities. Now $e$ is measured in volts and $C$ in ampères, the only undefined unit in the above expression being that of resistance. For simplicity, let us define the unit of resistance to be that of a wire through which one ampère will flow under a pressure of one volt maintained at the ends. With this definition $K$ becomes unity, and the resistance $r$ of a wire through which $C$ ampères flow, under a pressure of $e$ volts at the ends, is

$$r = \frac{e}{C}.$$

The unit of resistance thus defined is called an **ohm**, and is equal to the resistance of a column of pure mercury at 0°C, whose length is 106·3 cm. and sectional area 1 sq. mm.

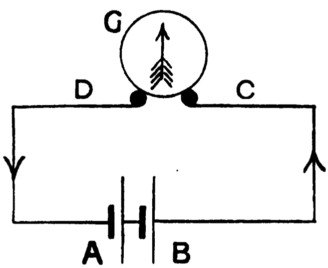

Fig. 7.

Suppose now we have a complete circuit, as in Fig. 7, where $AB$ is a battery of two cells in series joined to a galvanoscope $G$. The current passes in the direction of the arrow-heads, and there is a continual fall of potential through the battery from $A$ to $B$ and round the circuit back to $A$. If the fall of potential between $A$ and $B$ is indicated by $e^A_B$, and the resistance of the battery by $r^A_B$, with similar notation for the other parts of the circuit, we have

$$C = \frac{e^A_B}{r^A_B} = \frac{e^B_C}{r^B_C} = \frac{e^C_D}{r^C_D} = \frac{e^D_A}{r^D_A}$$

$$= \frac{\text{sum of numerators}}{\text{sum of denominators}} \text{ (by Algebra),}$$

$$= \frac{\text{total fall of potential}}{\text{total resistance in circuit}},$$

$$\therefore \quad C = \frac{E}{R} \text{ or } CR = E, \qquad \text{(ii)}$$

where $E$ is the E.M.F. of the battery, and $R$ the total resistance; or calling the resistances of the battery, galvanometer, and leads[15], $B$, $G$, $r$ respectively,

$$C = \frac{E}{B+G+r}.$$

This relation expresses **Ohm's Law,** and was experimentally proved by Ohm, who was led to it by considering the analogous phenomena of conduction of heat. It is the basis of experimental work in Current Electricity.

N.B. If any of the resistances in circuit are very small compared with that of the other parts of the circuit they may be neglected, as the value of the current will be practically unaltered by so doing. Thus, if in Fig. 7 the E.M.F. of the battery is 4 volts, its resistance 3 ohms, and that of the galvanometer 200 ohms, and that of the leads together ·1 ohm, taking into account the resistance of the leads we get, by substituting known quantities in the last equation,

$$C = \frac{4}{203 \cdot 1} = \cdot 01969 \text{ ampères.}$$

Neglecting the leads,

$$C = \frac{4}{203} = \cdot 0127 \text{ ampères,}$$

a difference only of 1 in 2000 nearly, or ·05 %.

**Box of Resistance Coils.** To weigh bodies by the ordinary balance we employ a box of masses containing multiples of the unit of mass, the gram. To measure resistances we employ a box of resistance coils containing coils of wire whose resistances are multiples of the unit of resistance, the ohm. With an ordinary resistance box we have a range from 1—10,000 ohms. To prevent as much as possible the heating effect of the currents which would tend to alter the face values of the resistances, the wires are of German silver or platinoid, the lower resistances being of thicker, the higher of

[15] Wires used merely to connect the different parts of a circuit are called 'leads.' Copper wire of B.W.G. 20, tinned, insulated by indiarubber, and covered with cotton may be used, its resistance being very small.

thinner wires. Each wire is bent in the middle, and starting from there, both parts are wound together on a wooden or ebonite bobbin, the coil being saturated with paraffin wax to prevent short circuiting between neighbouring turns. On the top of the box is a number of thick brass pieces, separated by narrow spaces into which brass plugs fit. To each brass piece is soldered one end of two successive coils, and numbers indicating the values of the resistances in ohms are placed close to the plug holes. If the resistance box forms part of a circuit when all the plugs are in their holes, the entire current passes through the thick brass pieces, which practically offer no resistance. If plugs are taken out resistances are introduced into

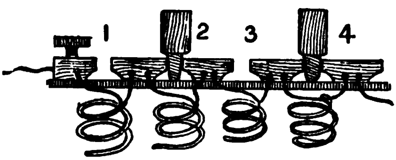


Fig. 8.

the circuit, the current having to pass through the corresponding resistance coils. In Fig. 8, showing a portion of a box of coils, if all the plugs are in except the two shown wanting, 4 ohms have been introduced into the circuit. In such a box of coils we can only vary the resistance *per saltum.* To vary it continuously we must use some sort of 'rheostat' or its equivalent. A convenient form is the copper sulphate rheostat described on p. 73, when the resistance introduced is not required to be known. By raising or lowering the electrode the current may be varied within limits as required. In cases where it is required to know the value of the resistance, we may use a length of German silver or of copper wire, whose resistance per metre is known.

**Wheatstone's Bridge.** Fig. 9 is a diagram of a Wheatstone's bridge for measuring resistances. $E$ is a cell whose poles are joined to the ends $A$, $B$ of a wire laid along a metre scale. To the points $A$, $C$ are joined the ends of the wire $X$, whose resistance is to be measured; to $C$, $B$, the terminals of

the resistance box $R$, and to $C$ is also joined one terminal of a galvanoscope. To the other terminal of the latter is attached a wire, with the free end of which contact can be made at any point along the wire $AB$. The current, on reaching $A$, divides into two portions, one flowing round $ACB$, the other along the wire $AB$, and both will unite at $B$ and so return to the cell. If contact is made at any point $D$, in general a part of the upper current will branch off at $C$, go through the galvanoscope, deflecting the needle in one direction, and return to the cell along $DB$, or else a part of the lower current will branch off at $D$, go through the galvanoscope, deflecting the needle in the opposite direction, and return to the cell along $CB$. Hence there is some point between $AB$ at which, if contact is made, no current goes through the galvanoscope, which remains undeflected. Suppose contact is made at such a point $D$, which is unique, and if $R$ is the resistance introduced from the resistance box, then

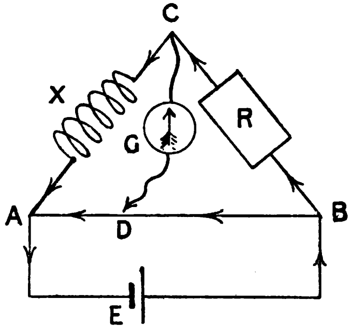


Fig. 9.

$$\frac{X}{R} = \frac{AD}{DB} \text{ or } X = \frac{a}{b} R \text{ ohms.} \qquad \text{(iii)}$$

That it is possible to find such a point, and that, when found, the above relations hold, is easily seen as follows:—

Draw a vertical $AE$ (Fig. 10) to represent the difference of potential between $A$ and $B$, which forces the upper portion of the current through $ACB$, and the lower through $AB$. Along a horizontal through $A$ lay off lengths $AC$, $CB$ to the right, proportional to the resistances $X$ and $R$ respectively, and to the left a length $AB'$, proportional to the resistance of the wire $AB$ on the same scale. Through $C$ draw vertical $CC'$, meeting $EB$ in $C'$. The length of this line represents the

difference of potential between $C$ and $B$ (Fig. 9). Through $C'$ draw $C'D'$ horizontal, meeting $EB'$ at $D'$, and draw the

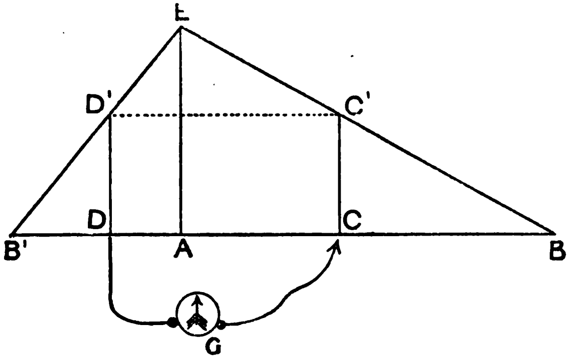


Fig. 10.

vertical $D'D$. Since $DD' = CC'$, the potential at $D$ is the same as that at $C$, so that no current will flow through a galvanoscope joined to $C$ and $D$. By the geometry of the figure we see that

$$\frac{AC}{CB} \text{ or } \frac{X}{R} = \frac{AD}{DB'}.$$

Thus the unknown resistance, $X$, bears the same proportion to the known resistance, $R$, as the corresponding lengths into which the wire, $AB$, is divided by the point, $D$, when no current passes through the galvanometer.

The galvanoscope and battery may be interchanged[16] in position, as when there is no current through the former the branches containing the two are independent of each other, and are said to be 'conjugate.'

The simplest practical form of the Wheatstone's bridge is called the metre bridge, and is seen in Fig. 11, where the letters correspond to those in Fig. 9. $AB$ is a wire of German silver or platinoid, about No. 16 B.W.G., laid along a metre rule screwed to a heavy base-board. The ends $A$, $B$ are soldered to two thick L-shaped copper pieces, each of which carry two

[16] In very accurate experiments the galvanometer or the battery, whichever of the two has the greater resistance, is joined to the junction of the two larger and to the junction of the two smaller arm resistances, as it can be proved that this arrangement is the best.

terminals. A third copper piece in the middle carries three terminals. The wires joined to a copper piece are practically

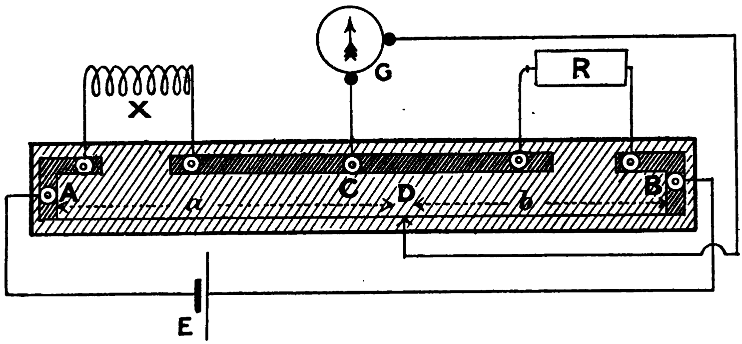


Fig. 11.

joined to the same point, and the arrangement in the two figures [17] will be found to be the same on comparing them.

In using the metre bridge (i) the leads joining both the box of coils and the resistance to be measured to the bridge must be of thick copper wire of negligible resistance. (ii) All connexions between wires and terminals must be scraped clean and bright, and care must be taken that the terminals bite the uninsulated parts of the wire. (iii) The galvanoscope must be levelled so that the needle swings freely, and the coil must be placed in the magnetic meridian. (iv) It is best to use a low or a high resistance galvanoscope according as we are measuring low or high resistances. In cases where a sliding contact is to be made it is well to attach the free end of the wire to a terminal joined to a blunt knife-edge of steel.

**3. To prove that the resistance of a conductor varies directly as its length and inversely as its sectional area.**

*Apparatus.* Metre Bridge: German Silver Wire of B.W.G. 22 and 25: a Low-resistance Galvanoscope: a Screw Gauge: a Metre Rule: a Bichromate Cell.

[17] In drawing diagrams of circuits the leads should be drawn as straight lines bent at right angles, and, where leads cross, one should be curved as shown in the figure.

*Experiment.* (i) Measure off two lengths of the wire, one 102, the other 152 cm., and scrape off the insulation, exposing 1 cm. of the wires at the ends. Attach the cell and the galvanoscope (whose coil must be in the magnetic meridian) to the bridge, as in Fig. 11, and the wires in the gaps $AC$ and $BC$, so that there is exactly 1 metre of one wire and 1½ metre of the other between its pair of terminals. Find the point of contact $D$[18] at which the needle is undeflected. The two parts into which the point $D$ divides $AB$ are in the same proportion as the resistances of the two wires on the corresponding sides of the bridge. This proportion will be found to be as 2 : 3, the same as that of the lengths of the wires. (ii) Measure off 102 cm. of each gauge of wire and scrape the insulation off, exposing 1 cm. of the wires at the ends. Attach the cell and galvanoscope (whose coil must be in the magnetic meridian) to the bridge, as in Fig. 11, and the wires in the gaps $AC$ and $BC$, so that there is exactly one metre of each wire between its pair of terminals. Find the zero point $D$. The two parts into which the point $D$ divides $AB$ are in the same proportion as the resistances of the two wires on the corresponding sides of the bridge. Measure carefully with the screw gauge the diameter of the uncovered part of each wire. The diameter should be measured in two or three places and the average taken. The ratio between the squares of the diameters, which are proportional to the sectional areas, will be found in the inverse ratio of the corresponding resistances.

**4. To measure the resistance of a wire, and to determine the specific resistance of the material.**

*Apparatus.* Metre Bridge: a Low-resistance Galvanoscope: a Box of Coils: about four metres each of German Silver Wire of B.W.G. 22 and 25: a Screw Gauge: a Metre Rule: two Bichromate Cells.

*Experiment.* (i) Scrape the insulation off the ends of one of the wires and arrange the apparatus as in Fig. 11, where $X$ is the wire, $R$ the box of coils, $E$ the cell, $G$ the galvanoscope.

[18] We shall call such a point the zero point in future.

See that all connexions between wires and terminals are bright and clean. Place the coil of the galvanoscope in the magnetic meridian and level it so that the needle swings freely. We should always test whether the connexions have been properly made as follows:—With all the plugs in the box of coils make momentary contact at the middle of the wire $AB$. The needle will be deflected in one direction. Now take the infinite plug out, marked INF, which breaks the circuit through the box of coils, and again making momentary contact at the middle point of the wire, we should get a deflexion in the other direction. If this is not so, either our connexions are wrong and should be looked to, or one of the connecting wires is broken and must be replaced[19]. Introduce a suitable resistance from the box of coils (in this case about 3 ohms) and find the zero point. It can be proved that least error is made in the result when this point is at the middle of the wire (Appendix A, 1). If, therefore, it is some distance from the middle we must alter the resistance introduced from the box, so as to bring the point nearer the middle. If the longer of the two lengths into which the point divides the metre wire is on the side of the box of coils, the resistance introduced is too large, and vice versa. Alter the resistance until the point is near the middle of the wire and determine its position carefully. A still more accurate determination may now be made by using two cells joined in series. If $R$ is the resistance introduced, and the point of contact divides the wire $AB$ into segments of lengths $a$, $b$, then

$$X = \frac{a}{b} R \text{ ohms.}$$

It is well to alter the resistance from the box by an ohm or so and repeat the experiment, and to take the average of the values as the true resistance required. Calculate the resistance per metre of each of the two gauges of wires. These results will

[19] If we know, within certain limits, the value of the resistance to be measured, a better method of testing whether the connexions are right is to introduce an approximate resistance from the box of coils, and then to make momentary contact first with one end and then with the other end of the metre wire. The deflexions ought to be in opposite directions.

be required in subsequent experiments. (ii) Measure the exact length between the terminals of the bridge of one of the German silver wires, whose resistance, $r$, was determined in the last experiment. With the screw gauge find the diameter of the uninsulated wire in two or three places, and take the mean as the true diameter. Calculate the sectional area, $a$ (or $\pi r^2$), and determine the specific resistance, $k$, of German silver by substituting for known quantities in

$$k = \frac{ar}{l}. \quad \text{(See Equation i.)}$$

Repeat for the other wire and compare your results.

Wires are said to be joined ($a$) in *series* if they are connected end to end successively so that the whole current passes through each of them; ($b$) in *multiple* or *parallel* when joined as in

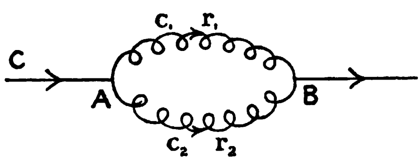


Fig. 12.

Fig. 12, so that the main current divides and a part goes through each.

The **equivalent resistance** of a system of wires is the resistance of that single wire which can replace the system in the circuit *without altering the value of the main current.*

**5. To prove that the equivalent resistance of wires joined in series is equal to the sum of their separate resistances.**

*Apparatus.* Metre Bridge: two Resistance Coils of about 50 and 80 ohms: a High-resistance Galvanoscope: a Resistance Box of Coils: two Bichromate Cells.

*Experiment.* Measure very carefully, as in Experiment 4, the resistances, $r_1, r_2$, of each coil separately. Join the coils in series

by a clamp, and, as before, measure the combined resistance, $r$, of the two, and enter your results in the left-hand column of the tabular form in the next experiment.

Take a third coil about 100 ohms, measure its resistance, join it in series to the other two, and measure the combined resistance, and again prove the above relation.

**6. To prove that the equivalent resistance, $r$, of wires joined in parallel arc is such that its reciprocal is equal to the sum of the reciprocals of the individual resistances, $r_1$, $r_2$, ..., or that**

$$\frac{1}{r}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}\cdots.$$

*Apparatus.* Same as in Experiment 4.

*Experiment.* In the case of two coils, the relation to be proved is

$$\frac{1}{r}=\frac{1}{r_1}+\frac{1}{r_2},$$

$$\text{or}\quad r=\frac{r_1 r_2}{r_1+r_2}.$$

Join up the two coils, whose resistances, $r_1$, $r_2$, were determined in the last experiment, in parallel arc. Wind another piece of the wire round the remaining two terminals, join the ends of the wires to the metre bridge, and measure as before the combined resistance, $r$, and enter your results in the right-hand column of the following tabular form:—

| In Series | In Parallel |
|---|---|
| $r_1 =$ ... <br> $r_2 =$ ... <br> Sum = ... | $r_1 r_2 =$ ... <br> $r_1 + r_2 =$ ... <br> Quotient = ... |
| Equivalent resistance as measured on bridge | |
| ... | ... |

Now join three resistances in parallel arc and again prove the above relation.

It is evident that the equivalent resistance of a system of wires joined in parallel arc is less than either of the individual resistances[20]. This may be shown graphically as follows:—

Take a straight line *AB* (Fig. 13) of any given length. Erect perpendiculars *AC*, *BD* at the ends, to represent on the same

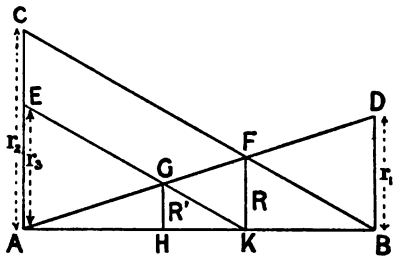


Fig. 13.

scale two resistances, $r_2$, $r_1$, joined in multiple arc. Join *CB* and *DA*, intersecting at *F*. Then *FK*, perpendicular to *AB*, will represent on the same scale their equivalent resistance.

For $$\frac{AB}{r_2} = \frac{BK}{R} \quad \text{and} \quad \frac{AB}{r_1} = \frac{AK}{R}.$$

Adding we have $$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}.$$

Similarly, in the case of three wires, $r_1$, $r_2$, $r_3$, in multiple arc, if *AE* represents the resistance $r_3$. Join *EK*, cutting *FA* at G, then *GH* represents the equivalent resistance.

**Division of the Main Current.** Let *C* be the main current, and $c_1$, $c_2$ the portions into which it divides on passing between two points *A* and *B*, joined by two wires in parallel arc, whose resistances are $r_1$, $r_2$. (See Fig. 12.)

[20] In the case of *n* wires joined in parallel arc it can be shown that the equivalent resistance of the system is equal to

$$\frac{\text{product of the individual resistances}}{\text{sum of the combinations of the } n \text{ resistances taken } \overline{n-1} \text{ together}}.$$

If $e$ is the difference of potential between $A$ and $B$, then, by Ohm's Law (Equation ii), we have

$$e = c_1 r_1 = c_2 r_2 \quad \text{or} \quad \frac{c_1}{c_2} = \frac{r_2}{r_1},$$

i.e. the currents vary inversely as the resistances of the wires through which they pass.

Again, $$c_1 + c_2 = C,$$

$$\therefore \quad c_1 = \frac{r_2}{r_1 + r_2} C \quad \text{and} \quad c_2 = \frac{r_1}{r_1 + r_2} C.$$

**Shunts.** The deflexion produced by a current through a galvanometer is lessened if we join its terminals by a wire[21], as a portion of the main current is 'shunted,' i.e. passes through the wire. The less the resistance of the shunt the greater the current that passes through it and the less the current that passes through the galvanometer. If $G$, $S$ are the resistances of the galvanometer and the shunt, then $C_G$, $C_S$, the portions of the main current $C$ that pass through the galvanometer and the shunt respectively, are according to the above,

$$C_G = \frac{S}{G+S} C,$$

$$C_S = \frac{G}{G+S} C.$$

**7. To measure the resistance of a galvanoscope by its own deflexion (Thomson's Method).**

*Apparatus.* Metre Bridge: a High-resistance Galvanoscope: a Box of Coils: German Silver Wire about B.W.G. 22: a Bichromate Cell.

*Experiment.* Insert the galvanoscope whose resistance is to be measured in the left gap, the box of coils in the right gap of the bridge, and attach the cell to the usual terminals. Join one

[21] It must be remembered that by shunting the galvanometer the main current is increased, as the equivalent resistance of $\frac{GS}{G+S}$ of the shunted galvanometer is less than that of the galvanometer alone.

end of a long piece of wire to the remaining terminal at $C$, so that with the free end we can touch along $AB$. Whether contact is made or not, the galvanoscope is in a closed circuit, and a current passes through it, as may be seen on drawing a diagram of the arrangement similar to Fig. 9. If the deflexion of the needle is very great, shunt the cell, by fixing one end of an uncovered German silver wire to one of its terminals and passing the wire through the other terminal. Alter the length of the shunt till the deflexion is about 60°. Introduce from the box of coils a resistance not very different to that of the galvanoscope. Test whether your connexions are right by touching successively the two ends of $AB$. The deflexion should be in the one case greater than, in the other case less than, its original value. Hence, at some intermediate point, contact can be made without altering the original deflexion. Find this point of contact carefully. If it is some distance from the middle, introduce a greater or smaller resistance from the box, so as to bring it as near the middle as you can. If $R$ is the resistance introduced, and if the point of contact divides $AB$ into segments of lengths $a$, $b$, the resistance of the galvanoscope is given by

$$G = \frac{a}{b} R \text{ ohms.}$$

Two more determinations should be made in each case, varying $R$ by an ohm, and the average taken as the true resistance.

N.B. In the case of a galvanoscope of less than one ohm resistance, when using a box of coils in which the least resistance is one ohm, the point of contact may be some distance from the middle. A more accurate result in this case is obtained if we replace the box of coils by a length of uncovered German silver wire, whose resistance per metre is known. Fixing one end to the one terminal, find the length required, so that no alteration is produced in the deflexion of the galvanoscope, when the point of contact is at the middle of $AB$. Calculate the resistance of this length, which is that of the galvanoscope.

**8. To measure the resistance of a battery cell by Mance's method.**

*Apparatus.* Metre Bridge: a Low-resistance Galvanoscope: a Box of Coils: Different kinds of Cells.

*Experiment.* Interchange the positions of the cell and galvanoscope in the last experiment. In this case also a current always passes through the galvanoscope. If the deflexion is too great, shunt the galvanoscope till it is reduced to about 60°. Proceed exactly as in the last experiment. If $R$ is the resistance introduced from the box of coils (1 ohm probably), and if the point of contact divides the wire into segments of lengths $a$, $b$, the resistance of the cell is given by

$$B = \frac{a}{b} R \text{ ohms.}$$

Measure the resistance of each cell as above. Join two or three similar cells in series, and prove that the combined resistance is two or three times that of one cell. Join two or three in parallel (i.e. join similar poles together), and show that the combined resistance is half or a third that of one cell respectively.

N.B. In the case of a cell whose resistance is much less than an ohm, it is better to employ the substituted wire method as explained in Experiment 7 for a low-resistance galvanometer.

The accuracy of this method depends on the assumption that the E.M.F. of the cell remains constant. The resistance of a cell, also, alters while it sends a current in consequence of the chemical changes that take place within it. The resistance we measure is therefore that at the particular moment the correct contact is made. Again, since when contact is made, another branch is offered for the current to pass along, the equivalent resistance of the system of wires is lessened; hence the current is greater before than after contact is made.

**9. To find the resistance of a given column of an electrolyte, and hence to determine its specific conductivity by Horsford's method.**

*Apparatus.* A Box of Coils: a High-resistance Galvanoscope: a Contact Key: a Rheostat made as described below to contain the Electrolyte: a 20% solution of Copper Sulphate: a Thermometer: two Bichromates joined in series.

[Fig. 14. *T* is a glass tube about 30 cm. long and 3 cm. in diameter, closed at each end by a one-holed bung. At the bottom of the tube is a copper disk, *B*, connected to a thick copper wire passing through the lower bung, and for convenience bent at right angles, so that the apparatus may be fixed to a board in a vertical position. *A* is another copper disk, of exactly the same size as *B*, fixed centrally to a thick copper wire long enough to allow the disk to be moved the whole length of the tube. This wire is insulated by being passed through a piece of glass quill tubing, attached to the wire at the lower end by a narrow piece of india-rubber tubing. The quill tube slides through the hole in the upper bung. Both wires carry clamps for connexion to the circuit. A paper scale of millimetres is gummed along the whole length of *T*.]

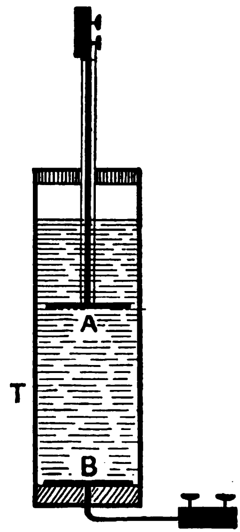

Fig. 14.

*Experiment.* Nearly fill *T* with the solution, and join it up in series with the rest of the apparatus[22]. Introduce from the box of coils a sufficient resistance to get a deflexion about 50° when the disks are as far apart as the liquid allows. Accurately read the position of *A* and the deflexion. Now introduce 10 more ohms from the box. The deflexion is decreased. Lower *A* until the original deflexion is obtained, and again read its position. The resistance of the column of the liquid between the two positions is 10 ohms[23].

[22] In using this apparatus always send the current downwards through the solution, so as to keep the plate at the bottom in good condition.

[23] On passing a current through an electrolyte its resistance alters owing to changes (polarization) in its condition near the electrodes. When the electrodes are composed of the metal forming the base of the salt the polarizing effects are small. We assume that, since the current is the same when measurements are taken, the polarization is the same.

Introduce another 10 ohms, and repeat. Take as many readings thus as you can, and take the average of the lengths as that length, *l*, of the electrolyte whose resistance is 10 ohms. The observations should be made as quickly as possible, as the resistance alters with the temperature. Measure the diameter of the disk *A*, and calculate its area, *a*. By unitary method, or by substitution in Equation i, find *k*, the specific resistance, and its reciprocal, the specific conductivity of the solution. Find its density and temperature, and compare your result with that given in Appendix B, 4.

Determine as above the specific conductivities of solutions of copper sulphate of different densities, and plot a curve connecting them with the percentages by mass of copper sulphate dissolved.

N.B. We can use this same instrument for other electrolytes. In the case of a solution of a zinc salt the electrodes may be of zinc, in the case of a silver salt the copper electrodes may be covered with a deposit of silver by simple immersion in a solution of silver nitrate. In other cases we can cover the electrodes with platinum black, by placing them in a very dilute solution of chloroplatinic acid and passing between them an electric current under a pressure of 4 or 5 volts, changing the direction of the current occasionally. The electrodes should be thoroughly washed afterwards, as the platinizing solution adheres with great obstinacy to the coating.

***10. To measure the specific conductivity of an electrolyte by the differential cell.**

*Apparatus.* Metre Bridge: the differential Electrolytic Cell (Fig. 15): a High-resistance Galvanoscope: a Box of Coils: one or two Bichromates.

*Experiment.* In order to eliminate polarization effects at the electrodes, the differential form of electrolytic cell (Fig. 15) may be used. It consists of a wide glass U-tube, into one arm of which another tube has been fused. The three openings, *A*, *B*, *C*, are closed by bungs, through which narrow glass

tubes pass. Through the closed end of each tube is fused a piece of platinum wire carrying an electrode dipping into the electrolyte. Connexion with the circuit is made, as in Fig. 6, by filling the narrow glass tubes with mercury. On measuring the resistance of the electrolyte, first between $A$ and $B$, and then between $A$ and $C$, we can by subtraction eliminate the polarization effects at the electrodes, and obtain the resistance of a column of the liquid equal to the difference of the two columns measured.

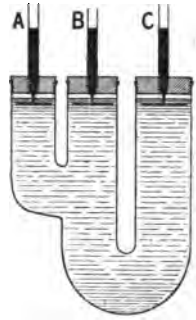


Fig. 15.

To find the specific conductivity of an electrolyte, we must first find the 'capacity' of the cell by employing an electrolyte whose specific conductivity is known. Fill the cell with a solution of zinc sulphate of known strength at a given temperature. Let $K$ be its specific conductivity, i.e. the reciprocal of its specific resistance as given in Appendix B, 4, and $r$ the resistance of the difference of the two columns of the solution as measured above, and $C$ the capacity of the cell, then

$$r = \frac{C}{K} \quad \text{or} \quad C = Kr,$$

a known quantity. If $r'$ is the resistance of this difference column of any other electrolyte, its specific conductivity

$$K' = \frac{C}{r'}.$$

Find the specific conductivity of the solution of copper sulphate used in the last experiment, and compare your results.

## D. The Tangent Galvanometer and its Use.

**The Tangent Galvanometer.** Instruments in which there is a simple relation between the strength of a current and the angle through which it deflects a compass needle from the magnetic meridian are called Galvanometers[24], since by means of them currents can be compared or measured. We have seen above (Fig. 4) that a current, sent round a circular coil, sends out lines of force perpendicular to the plane of the coil. The field at the centre, in which a short magnetic needle swings, may be considered uniform, and if the coil is in the magnetic meridian, and the needle is deflected an angle $a$ from the meridian by the current, the intensity of the field at the centre, which is proportional to the strength of the current $C$, varies as $\tan a$ (*Magnetism*, p. 18),

$$\therefore \quad C = K \tan a,$$

where $K$ is called the 'reduction factor' of the galvanometer, and is the number by which we must multiply $\tan a$ to get the strength of the current, or is the value of the current in suitable units which causes a deflexion of 45°.

An instrument as above constructed, with a short magnetic needle suspended at the centre of a circular coil, is called a 'Tangent Galvanometer.' It is convenient to have it made with two or more separate coils consisting of different numbers of turns of wire, each coil having a separate pair of terminals, so that we can use the same instrument for strong or weak currents, each coil having of course a different reduction factor. The needle is suspended at the centre of a graduated circle, and has a pointer attached at right angles to its length, the ends of which move over the graduations. The four quadrants of the circle are graduated from 0° to 90°, in such a way that the zeros are in the same straight line. The inner portion of the circle is

[24] A galvanometer is indicated in diagrammatic form as in Fig. 17 at $G$.

cut away, exposing the plane mirror forming its support. As in the magnetometer (p. 20) we avoid parallax in reading the angles, and the average of four angles is to be taken as the angle of deflexion, viz. the angles made by the two ends of the pointer before and after reversing the direction of the current (Note 13, p. 21). Before using the galvanometer we must level it so that the needle swings freely, and the coil must be placed exactly in the magnetic meridian. When this is the case the pointer should lie along the line of zeros. The direction of the current is reversed by means of a 'commutator.' A convenient form, Pohl's, is given in Fig. 16.

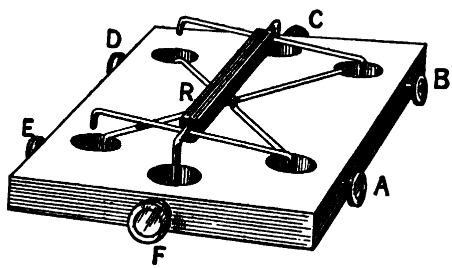


Fig. 16.

*A, B, C, D, E, F* are mercury cups with terminals attached. *A* is connected to *D*, and *B* to *E*, by cross wires which do not touch each other. A rocker, *R*, consists of two semicircular pieces of wire, separated by an insulating rod, and connected respectively to the terminals *C*, *F*, in which they are pivoted. If *A*, *B* are joined to the terminals of the galvanometer, and *C*, *F* to the main circuit, then, in the position indicated in the figure, the current, supposed to enter at *C*, passes to *B*, round galvanometer, to *A*, and out at *F*. If the rocker is turned over so that its other two ends dip into the cups *D*, *E*, the direction of the current is *CDA*, round galvanometer in opposite direction, to *BE*, and out at *F*. The ends of all the wires of the instrument should be amalgamated by being dipped into a solution of mercury perchloride.

**11. To prove that the strength of a current varies as the tangent of the angle of deflexion in a tangent galvanometer.**

*Apparatus.* Tangent Galvanometer of known resistance: a Box of Coils: a Plug Key: a Commutator: Curve Paper: one or two constant Daniell's Cells, whose resistances are known.

*Experiment.* By Ohm's Law, if the E.M.F. is constant, $C \propto \frac{1}{R}$, where $R$ is the total resistance of the circuit. Hence we have to prove that $\tan a \propto \frac{1}{R}$ or that $R \tan a$ is constant, if the E.M.F. of the battery does not alter during the experiment. The cells should be short circuited for five minutes before use. Join the terminals of the galvanometer to $A$, $B$ of the commutator, and the main leads to $C$ and $F$ (Fig. 16), and arrange the apparatus in series, employing one or two Daniell's cells, and such a coil that, when no resistance is introduced from the box, the deflexion is not greater than 70°[23]. Take the average of the readings of the ends of the pointer before and after reversing the current as the angle, $a$, of deflexion. Introducing successively increasing resistances, $r$, from the box of coils, repeat the above for as many angles of deflexion as possible, till the deflexion is reduced to about 25°, and enter your results in a tabular form as follows:—

| Resistance introduced $r$ | Total resistance in circuit $R=B+G+r$ | Readings of ends of pointer: Before reversal | | After reversal | | Mean angle of deflexion $a$ | $\tan a$ | $\frac{E}{K}$ or $R \tan a$ | $\frac{1}{R}$ | $K$ | Current in ampères $C$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. |
| .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. | .. |

[23] If the deflexion of the galvanometer is too great its terminals may be shunted with a convenient length of wire. If the resistance of the shunt is known as well as that of the galvanometer we can calculate by law of divided circuits the current that passes through the latter (p. 70).

$R \tan a$ should be constant. Plot a curve, taking the values of $\tan a$ as abscissae, and of $\frac{1}{R}$ as ordinates. It should evidently be a straight line. Finding the value of $E$ for the cells used from the tables (Appendix B, 2), deduce the value in each case for the reduction factor $K$, which should also be constant. From the equation $C = K \tan a$ calculate the current in ampères. Prove that $C \propto \frac{1}{R}$ by plotting another curve, taking the values of the currents as abscissae, and those for $\frac{1}{R}$ as ordinates.

**12. To calibrate a galvanoscope by a tangent galvanometer, i.e. to plot a curve showing the relation between the strength of the current and the deflexion it produces.**

*Apparatus.* A Tangent Galvanometer joined to a commutator: a Galvanoscope: a Rheostat: a Contact Key: Curve Paper: one or two Cells.

*Experiment.* Join up the apparatus in series, levelling the galvanometer and galvanoscope with their coils along the magnetic meridian, using one or both cells, so that by altering the resistance in circuit the deflexion on the tangent galvanometer may be varied from 0° to about 90°. If we find that the simultaneous deflexions on the two instruments do not cover approximately the same range, we shall have to shunt one or other of them until they do. The experiment consists in altering the resistance in circuit so as to get as many deflexions on the tangent galvanometer as possible between 0° and 90°, and noting the simultaneous deflexions on the two instruments before and after reversing the current. In each case the average of the four readings of the pointer or of the magnetic needle should be taken. Enter your results in a tabular form as on top of next page.

Plot a curve, with the values of $\tan a$ as abscissae, and the deflexions on the galvanoscope as ordinates. From this curve we can find the ratio of two currents producing given deflexions on the galvanoscope, and this instrument can be used in the

| Mean deflexions on galvanometer $a$ | tan $a$ | Mean deflexions on galvanoscope |
|---|---|---|
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |

numerous experiments in which two currents are to be compared whose strengths individually are not required to be known. If we use no shunt for the tangent galvanometer, and know its reduction factor, the curve so drawn will give us the value of the current in ampères that produce a given deflexion on the galvanoscope.

### 13. To calibrate a galvanoscope by Ohm's Law.

*Apparatus.* A Galvanoscope of known resistance: a Box of Coils: two or three constant Daniell's Cells.

*Experiment.* By Ohm's Law, if the E.M.F. of the battery is constant, the current strength varies inversely as the total resistance in circuit. Short circuit the Daniell's cells in series for two or three minutes. Join up the apparatus in series, using such a number of cells that when no resistance, or but a very small resistance, is introduced from the box, the deflexion on the galvanoscope is about 60° or 70°. The experiment consists in reading as many deflexions as possible as the resistance is gradually increased. Enter your results in a tabular form as follows:—

| Resistance introduced from box $r$ | $B + G$ | Total resistance in circuit $R$ | $\frac{1}{R}$ | Galvanoscope deflexions $a$ |
|---|---|---|---|---|
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |

Plot a curve, with the deflexions as ordinates, and the values of $\frac{1}{R}$ as abscissae.

**14. To prove the law of division of a current through a multiple arc.**

*Apparatus.* A Tangent Galvanometer of known resistance joined to a Commutator: two Resistance Coils about 5 and 10 ohms: a Box of Coils: a Contact Key: one or two constant Daniells.

*Experiment.* Short circuit the cells for five minutes, and arrange the apparatus as in Fig. 17. One end of each of

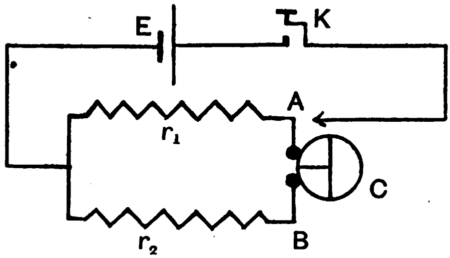


Fig. 17.

the resistances $r_1$, $r_2$ is joined to one pole of the battery, *E*, and the other ends are connected through the tangent galvanometer, *G*. If the free end of the wire from the other pole of the battery be joined to *B*, the current indicated by the galvanometer is that portion of the main current which passes through $r_1$ only. Find the average of the angles of deflexion before and after reversing the commutator. If the wire be joined to *A*, the current indicated by the galvanometer is that portion which passes through $r_2$. Let $a_2$ be the average angle of deflexion in this case. As the E.M.F. may not have kept quite constant, connect the wire to *B* again and take readings. Let $a_1$ be the average of the first and third set of readings. We shall find that $r_1 \tan a_1 = r_2 \tan a_2$,

$$\text{i. e. } \frac{C_1}{C_2} = \frac{r_2}{r_1},$$

or the currents in the two branches of a multiple arc are inversely proportional to the resistances of the two branches.

***15. To measure the sum of the resistances of a constant cell and a galvanometer, and hence to find the resistance of a given wire.**

*Apparatus.* A Tangent Galvanometer joined to a Commutator: a Contact Key: a Box of Coils: Unknown resistance: one or two constant Daniells.

*Experiment.* Short circuit the cells for five minutes. Arrange apparatus in series, omitting the unknown resistance. Choose such a coil of the galvanometer that by introducing a fairly small resistance, $r$, if necessary, from the box of coils, the angle of deflexion is about 60°. Read the average angle of deflexion, $a_1$. If the resistance required is too great we should use a controlling magnet placed in the magnetic meridian, in place of introducing a resistance to lessen the deflexion. The magnet must not be moved during the experiment. If $B$, $G$ be the resistances of battery and galvanometer respectively,

$$C_1 = \frac{E}{B+G+r_1} = K \tan a_1. \qquad (a)$$

Introduce more resistance to reduce the deflexion to about 45°, and read the average angle, $a_2$. Let $r_2$ be the total resistance introduced,

$$C_2 = \frac{E}{B+G+r_2} = K \tan a_2. \qquad (b)$$

Dividing one by the other we get

$$B+G = \frac{r_2 \tan a_2 - r_1 \tan a_1}{\tan a_1 - \tan a_2}.$$

Introduce the unknown resistance, $x$, into the circuit, and let $a_3$ be the average angle of deflexion when $r_1$ is introduced from the box, then

$$C'_1 = \frac{E}{B+G+r_1+x} = K \tan a_3. \qquad (c)$$

From $(a)$ and $(c)$ we get

$$x = \frac{\tan a_1 - \tan a_3}{\tan a_3}(B+G+r_1).$$

Knowing $B+G$ from above, we can find $x$.

Again, with $r_2$ introduced, let the angle of deflexion be $a'_3$ when $x$ is in circuit, then

$$x = \frac{\tan a_2 - \tan a'_3}{\tan a'_3}(B+G+r_2).$$

Compare your results for $x$.

An essential condition for this experiment is that the E.M.F. of the battery is constant.

**16. To measure the resistance of a constant cell, or of a galvanometer or a galvanoscope, by shunting with a known resistance (Thomson's reduced deflexion method).**

*Apparatus.* A Galvanometer[26]: a Box of Coils: Uncovered German Silver Wire of B.W.G. 25, whose resistance per metre is known: two Plug Keys: a constant Daniell.

*Experiment.* Arrange the apparatus as in Fig. 18, where $G$

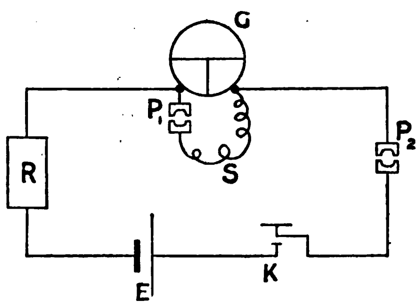


Fig. 18.

is the galvanometer, $R$ the box of coils, $E$ the cell, $K$ the contact key, $P_1$, $P_2$ plug keys, $S$ the shunt.

1. With the shunt not in circuit introduce a resistance, $r_1$, from the box of coils to give a deflexion of about 60°. If possible arrange that $r_1 = 0$, by using a controlling magnet placed in the magnetic meridian.

[26] A galvanoscope can be used instead of a galvanometer, since the current is the same in the two cases. It will be found that the same formulae apply if we shunt the cell instead of the galvanometer.

2. Introduce the wire shunt into the circuit by inserting the plug key $P_1$, and alter the length of the wire till the deflexion is reduced to about $45°$. Measure the length of the shunt and calculate its resistance, $S$. If $G$ is the resistance of the galvanometer, $\frac{GS}{G+S}$ is the equivalent resistance of the shunted galvanometer, and the fraction of the main current passing through the galvanometer is

$$\frac{S}{G+S} \times \frac{E}{B+\frac{GS}{G+S}+r_1}. \qquad \text{(See p. 70.)}$$

3. Unshunt the galvanometer and introduce a resistance from the box, and, if necessary, a length of the German silver wire across the plug key $P_2$, till the deflexion is the same as before. If $r_2$ is the total resistance introduced, the current through the galvanometer is

$$\frac{E}{B+G+r_2}.$$

Equating the values of the equal currents we get

$$B+r_1 = \frac{(r_2-r_1)\,S}{G},$$

$$\text{or} \quad G = \frac{(r_2-r_1)\,S}{B+r_1}.$$

If the galvanometer is a sensitive one, so that $r_1$ is great compared with $B$, we can neglect the latter.

An essential condition for this experiment is that the E.M.F. of the battery remains constant.

***17. To measure the resistance of a galvanometer by shunting it with two known resistances.**

*Apparatus.* A Tangent Galvanometer joined to a Commutator: a Plug Key: a Box of Coils: Uncovered German Silver Wire of B.W.G. 25: a Contact Key: one or two constant Daniells of known resistance.

*Experiment.* Short circuit the cells for five minutes and arrange the apparatus as in Fig. 18, so that the angle of deflexion is about 60°. Let $R$ be the resistance of the battery and the resistance, if any, introduced from the box. Shunt the galvanometer with a length of wire so as to reduce the deflexion

to about 45°. Read the average angle of deflexion $a_1$, and let the resistance of the shunt, as found from its length, be $S_1$, then

$$C_1 = \frac{S_1}{G+S_1} \times \frac{E}{R + \frac{GS_1}{G+S_1}} = K \tan a_1.$$

Shorten the length of wire shunt till the deflexion is reduced to about 30°, and let $S_2$, $a_2$ be the corresponding values:

$$C_2 = \frac{S_2}{G+S_2} \times \frac{E}{R + \frac{GS_2}{G+S_2}} = K \tan a_2.$$

From the above two equations we find that

$$G = \frac{\tan a_1 - \tan a_2}{\tan a_2 \left(\frac{1}{S_2} + \frac{1}{R}\right) - \tan a_1 \left(\frac{1}{S_1} + \frac{1}{R}\right)}.$$

If the galvanometer is a sensitive one, so that a large resistance has to be introduced from the box, $R$ being great, its reciprocal may be neglected, and

$$G = \frac{\tan a_1 - \tan a_2}{\frac{\tan a_2}{S_2} - \frac{\tan a_1}{S_1}}.$$

An essential condition for this experiment is that the E.M.F. of the battery remains constant.

**18. To find the reduction factor of a tangent galvanometer by deposition of copper.**

*Apparatus.* A Tangent Galvanometer joined to a Commutator: a Rheostat: an Electrolytic Cell with Copper Electrodes: a Plug Key: one or two Bichromates.

*Experiment.* Nearly fill the electrolytic cell with a saturated solution of copper sulphate, to which about $\frac{1}{10}$th of its volume of strong sulphuric acid has been added. Clean[27] the thin kathode and polish it with sand or emery paper. The portion to be immersed is on no account to be touched by the fingers. Connect the apparatus up in series, joining the kathode to the zinc pole of the battery. Make the circuit and vary the number

[27] See Note 11.

of cells and the resistance, so that there is a deflexion about 50° on the galvanometer. Break the circuit, take the kathode out, wash it in distilled water, then dip it in alcohol and dry it carefully over a Bunsen's flame, and weigh it as accurately as possible. Replace it in the cell, and at a given moment make the current. The current should be allowed to run for half an hour or more, and the deflexions of the needle read at equal intervals of time, say every two minutes, before and after reversing the current. Let $n$ be the number of seconds the current has been flowing, and $a$ the average angle of deflexion during the time. Take out the kathode, wash, dry, and weigh as before, and let $m$ be the increase of mass due to the deposited copper.

Now ·000326 grs. of Cu are deposited in 1 sec. by 1 ampère,

$$\therefore \quad m \text{ grs.} \quad ,, \quad ,, \quad \text{in } n \text{ sec. by } \frac{m}{\cdot 000326\, n} \text{ ampères}$$

$$= K \tan a,$$

$$\therefore \quad K = \frac{m}{\cdot 000326\, n \tan a}.$$

***19. To find the reduction factor of a tangent galvanometer by the volume voltameter.**

*Apparatus.* A Tangent Galvanometer joined to a Commutator: the Voltameter (Fig. 3): a Tube about 40 cm. closed at one end: a Rheostat[28]: a Plug Key: a Watch: a Thermometer: a Burette: two or three Bichromates.

*Experiment.* Nearly fill the voltameter with acidulated water, and connect it in series with the rest of the apparatus. Close the circuit and arrange the resistance of the circuit so that there is a deflexion of about 50°. Break the circuit and invert over the kathode of the voltameter the tube full of acidulated water, and fix it vertically in a clamp. At a given moment close the circuit and read the angles of deflexion at equal intervals of time, say every minute, both before and after reversing the current. Let the current pass until the level of the water inside

[28] Here, as elsewhere, a rheostat implies some means of introducing a variable resistance into a circuit to alter the strength of the current without necessarily knowing the value of the resistance. Either the copper sulphate rheostat may be employed, or a length of wire, or a box of coils, or a resistance board.

the tube is the same as that on the outside. Break the circuit and note the time during which the current has been passing. Let it be $n$ seconds, and let $a$ be the average angle of deflexion. Take the temperature, $t$, of the water and mark its level inside the tube by a piece of gummed paper, and find the volume, $V$, of the hydrogen by filling the tube up to the marked level with water from a graduated burette. Let the atmospheric pressure be $H$, as read by a barometer. To get the pressure of the dry hydrogen we must subtract from the atmospheric pressure the pressure of the vapour with which the gas was saturated, and which we may take to be the maximum aqueous vapour pressure, $F$, found from the tables (*Practical Work in Heat*, Appendix A, 10), for the temperature $t$. Since the volume of a given mass of gas varies directly as its absolute temperature, and inversely as its pressure, the volume $V$ of hydrogen at temperature, $t$, and at pressure, $H-F$, becomes, when reduced to $0°$ C. and 76 cm. of pressure,

$$\frac{273}{(273+t)}\frac{(H-F)}{76}V \text{ c.c.}$$

The mass $m$ of the hydrogen set free is found by multiplying the above fraction by $\cdot0000896$ grams, which is the mass of 1 c.c. of hydrogen at $0°$ and 76 cm.

Now $\cdot000011$ grs. of hydrogen is set free in 1 sec. by 1 ampère,

$$\therefore \quad m \text{ grs.} \quad ,, \quad ,, \quad ,, \quad n \text{ secs. by } \frac{m}{\cdot000011\,n} \text{ ampères}$$
$$= K \tan a.$$

Hence $$K = \frac{m}{\cdot000011\,n \tan a}.$$

**20. To compare electromotive forces by the sum and difference method.**

*Apparatus.* A Tangent Galvanometer joined to a Commutator: a Rheostat: a Contact Key: a constant Daniell: Leclanché, Grove, Bichromate Cells.

*Experiment.* Short circuit the Daniell for five minutes, then join it to a bichromate cell so that both cells tend to send a current in the same direction. Join them up with the rest of the apparatus in series, omitting the other two cells, choosing

such a coil of the galvanometer that there is a deflexion of about 60°, and, if necessary, make a final adjustment by introducing a resistance from the rheostat. Read the ends of the pointer before and after reversing the current, and let $a_1$ be the average angle of deflexion. If $E$, $E_1$ be the E.M.F.'s of the Daniell and bichromate respectively, the resultant E.M.F. is their sum $E_1+E$. If $R$ is the total resistance of the circuit,

$$C_1 = \frac{E+E_1}{R} = K \tan a_1.$$

Now reverse the poles of the Daniell so that the cells oppose each other, the resultant E.M.F. is $E_1-E$; if $a_2$ is the average angle of deflexion, since the total resistance is the same as before,

$$C_2 = \frac{E_1-E}{R} = K \tan a_2.$$

From the above two equations by division we get

$$\frac{E_1}{E} = \frac{\tan a_1 + \tan a_2}{\tan a_1 - \tan a_2}.$$

Taking $E$ as 1·1 volt, find the voltage of the bichromate. In a similar way find the voltage of the other cells, $E_2$, $E_3$.

To test the accuracy of your results find as above $\frac{E_1}{E_2}$ and $\frac{E_2}{E_3}$, and prove that

$$\frac{E_1}{E_2} \times \frac{E_2}{E_3} \times \frac{E_3}{E} = \frac{E_1}{E}.$$

**21. To determine the electromotive force of a constant cell by a tangent galvanometer of known reduction factor.**

*Apparatus.* A Tangent Galvanometer of known reduction factor joined to a Commutator: a Contact Key: a Box of Coils: a constant Daniell.

*Experiment.* Short circuit the cell for five minutes, then join up the apparatus in series. Introduce a resistance, $r_1$, from the box to obtain a deflexion of about 60°. Let the average angle of deflexion be $a_1$. Calculate the current $C_1 = K \tan a_1$ in ampères, then

$$C_1 = \frac{E}{B+G+r_1} = K \tan \alpha_1.$$

Increase the resistance to $r_2$, so that the angle of deflexion is reduced to about 30°, and let $\alpha_2$ be the average angle. Calculate the current $C_2$ in ampères; then

$$C_2 = \frac{E}{B+G+r_2} = K \tan \alpha_2.$$

From the above two equations we deduce that

$$E = \frac{C_1 C_2 (r_2 - r_1)}{C_1 - C_2} = \frac{K \tan \alpha_1 \tan \alpha_2 (r_2 - r_1)}{\tan \alpha_1 - \tan \alpha_2}.$$

Repeat the above by altering the resistances, and take the average value of the E.M.F. as that of the constant Daniell.

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## E. The Reflecting Galvanometer and its Use.

**The Reflecting Galvanometer.**—The reflecting galvanometer[29] is a more sensitive form of tangent galvanometer. A small mirror, at the back of which is attached by wax a small needle or astatic pair, is suspended by a single cocoon-fibre at the centre of a coil of wire of many turns and of small diameter. In front of the instrument is placed a horizontal scale about 50 cm. long, divided into millimetres. Below the zero is bored a hole in which fits one end of a brass tube carrying a lens. A fine vertical wire is stretched across the hole, and behind it is placed a paraffin lamp. When properly adjusted, the light passes through the lens, strikes the galvanometer mirror, is reflected back, and forms an image of the wire on the scale. The distance between the scale and the galvanometer depends on the focal length of the lens, and is in general about

[29] The reflecting galvanometer is diagrammatically represented as $G$ in Fig. 20.

a metre. On a vertical brass rod attached to the bobbin on which the coil is wound slides a magnet by means of which we can alter the strength of the magnetic field, controlling the needle so as to render the instrument more or less sensitive at will. Thus the field in which the needle swings is not that due to the earth alone, but the resultant field, due to the earth and the controlling magnet. As long as the resultant field is constant, the deflexion of the spot of light on the scale, when not too great, is proportional to the strength of the current through the galvanometer. With a delicate instrument such as the reflecting galvanometer, a shunt box is generally provided, containing shunts whose resistances are $\frac{1}{9}$th, $\frac{1}{99}$th, $\frac{1}{999}$th of the resistance of the galvanometer. By using one or other of them we can send through the galvanometer $\frac{1}{10}$th, $\frac{1}{100}$th, or $\frac{1}{1000}$th of the main current, as may be seen by introducing its value for $S$ in the expression for $C_G$, p. 70. It is important that the leads of the circuit should be so arranged that the current has no inductive action on the needle. The leads from the battery should be twisted together.

***22. To prove Ohm's Law (Method 1).**

*Apparatus.* A Reflecting Galvanometer of known resistance: a Box of Coils: a Plug Key: Uncovered German Silver Wire, whose resistance per metre is known: four or five constant Daniells.

*Experiment.* By Ohm's Law $\frac{E}{R}$ is constant when $C$ remains constant. Using all the cells, join up the apparatus in series, and introduce sufficient resistance, some thousands of ohms, from the box, so that the spot of light is deflected nearly to the end of the scale. Note the number, $n$, of cells used and the resistance introduced. Remove one cell and alter the resistance till you get the same deflexion, i.e. the same current, a length of the German silver wire being used for fractions of an ohm. Note the resistance introduced. Repeat this, removing one cell at a time, and enter your results in a tabular form as follows:—

| No. of cells used, $n$, proportional to $E$ | Resistance introduced $r$ | Total resistance of circuit $R$ | $\frac{n}{R}$ |
|---|---|---|---|
| ... | ... | ... | ... |
| ... | ... | ... | ... |
| ... | ... | ... | ... |

The battery resistance may be neglected in comparison with that of the rest of the circuit. The numbers in the last column should be constant.

### 23. To prove Ohm's Law (Method 2).

*Apparatus.* Same as in Experiment 22.

*Experiment.* By Ohm's Law $CR$ is constant if $E$ remains constant. Join up the apparatus in series, and introduce sufficient resistance from the box, so that the spot of light is deflected nearly to the end of the scale. Read the deflexion, which is proportional to the current. Introduce increasing resistances, and take as many readings of the corresponding deflexions as possible. Enter your results in a tabular form as follows:—

| Resistance introduced $r$ | Total resistance in circuit $R$ | Deflexions proportional to the currents $d$ | $\frac{1}{d}$ | $Rd$ |
|---|---|---|---|---|
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... |

The battery resistance may be neglected here also. The numbers in the last column should be constant. Plot a curve, with $\frac{1}{d}$ as ordinates, and $R$ as abscissae, and show how it proves the law.

***24. To prove Ohm's Law (Method 3).**

*Apparatus.* Same as in Experiment 22.

*Experiment.* By Ohm's Law $\frac{E}{C}$ is constant when $R$ remains constant. Using all the cells, join up the apparatus in series, and introduce sufficient resistance from the box, so that the spot of light is deflected nearly to the end of the scale. Note the number, $n$, of cells used and the deflexion, which is proportional to the current. Remove one cell at a time, and note the resulting deflexions, and enter your results in a tabular form as follows:—

| No. of cells used, $n$, proportional to $E$ | Deflexions proportional to currents $d$ | $\frac{E}{d}$ |
|---|---|---|
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |

The resistances of the cells are negligible, hence we have practically kept the resistance of the circuit the same throughout, and the numbers in the last column should be constant.

**25. To measure the resistance of the reflecting galvanometer and of a battery cell by shunting one of them.**

*Apparatus.* A Reflecting Galvanometer: Uncovered Copper and German Silver Wires of B.W.G. 25: a Box of Coils: a Plug Key: two constant Daniells.

*Experiment.* (i) *To find B.* Omitting the box of coils, arrange one cell, the key, and galvanometer in series: shunt the galvanometer with copper wire until the spot is deflected nearly to the end of the scale. The resistance of the shunt required is very small, as the galvanometer is very sensitive, and since the equivalent resistance of the shunted galvanometer is less than that of the shunt (p. 69), it may be neglected as compared with the resistance of the cell. Break the circuit. To one

terminal of the plug key join one end of the German silver wire, and passing the wire through the other terminal, find what length is necessary to reduce the deflexion to exactly one half. The known resistance of this length is equal to that of the cell, since the current has been halved.

Measure as above the resistance of each of the two cells, separately, and when joined in series, and when in parallel arc, and prove that the equivalent resistances obey the laws of Experiments 5 and 6.

(ii) *To find G.* Introduce the box of coils into the circuit, and shunt the cell with copper wire until the spot is deflected nearly to the end of the scale. The equivalent resistance of the shunted cell is so small that it may be neglected in comparison with that of the galvanometer. Proceed as above, introducing resistances from the box to reduce the deflexion to exactly one half. Resistances less than an ohm may be introduced by the German silver wire as above. The total resistance introduced is that of the galvanometer[30].

### 26. To determine the resistance of a cell by shunting it with a known resistance.

*Apparatus.* A Reflecting Galvanometer: a Box of Coils: Uncovered German Silver Wire of B.W.G. 22: a Contact Key: different kinds of Cells.

*Experiment.* Arrange the apparatus in series and introduce a resistance, some thousands of ohms, so that the spot is deflected nearly to the end of the scale. Read the deflexion, $d_1$. Since the resistance is very great the current is very small; therefore we may take the P.D. at the terminals of the cell (p. 45) to be practically equal to its E.M.F., $E$, on open circuit. Shunt the cell with the wire[31] until the deflexion is reduced to about half. Read the deflexion, $d_2$. Measure the length of

[30] The experiment should be done as quickly as possible, and the circuit should only be closed when a reading is being taken, as the resistance of a cell tends to alter when sending a large current, as it does through the low-resistance shunt.

[31] An additional terminal attached to one of the plates is convenient when the length of the shunt has to be adjusted.

the shunt and calculate its resistance, $r$. The P.D., $e$, between the terminals of the cell is that sending the current through the resistance $r$, and this P.D. is proportional to the deflexion $d_2$: $E-e$ is the P.D. driving the current through the cell itself. Therefore, by Ohm's Law,

$$\frac{E-e}{B}=\frac{e}{r}, \quad \text{or} \quad \frac{d_1-d_2}{B}=\frac{d_2}{r}, \quad \text{or} \quad B=r\frac{d_1-d_2}{d_2}.$$

Repeat the experiment, altering the resistance and the shunt, and take the average of the results.

Measure as above the resistance of a similar cell. Then join the two cells in series and then in parallel, measuring the equivalent resistance in the two cases, and compare your results with those calculated (Experiments 5 and 6). In this experiment the galvanometer with the high resistance in circuit is used as a voltmeter.

**27. To compare electromotive forces by the high-resistance method.**

*Apparatus.* A Reflecting Galvanometer: two Contact Keys: a Box of Coils: a constant Daniell: Bichromate: Leclanché: Grove.

*Experiment.* Short circuit the Daniell for five minutes. Join one terminal of the galvanometer to the box of coils, the other to one terminal of each of two contact keys. The other terminal of the box of coils join to the similar poles of the Daniell and bichromate cells, the other poles of the cells to be joined respectively to the remaining terminals of the two keys. By this means we can close the circuit through either one of the two cells at will. Introduce resistance from the box of coils, some thousands of ohms, so that on closing the bichromate circuit the spot is deflected nearly to the end of the scale. Read the deflexion, $d_1$. Next close the Daniell circuit and read the deflexion, $d$. These readings should be repeated a second time. Since the resistance introduced is very great, (i) the current is very small, therefore polarization need not be feared, and the difference of potential sending it through the galvanometer may be taken to be the same as the E.M.F. of

the cell on open circuit; (ii) the substitution of one cell for another makes no appreciable difference in the total resistance of the circuit, hence the currents, or the corresponding deflexions, are proportional to the E.M.F.'s of the cells. Hence, if $E_1$, $E$, are the E.M.F.'s of the bichromate and Daniell respectively,

$$\frac{E_1}{E} = \frac{d_1}{d}.$$

Taking $E$ as 1·1 volt, calculate the voltage of the bichromate. In a similar way find those of the other cells, and test the accuracy of your measurements as in Experiment 20. In this experiment the galvanometer in the high-resistance circuit is used as a voltmeter.

***28. To calibrate the metre bridge wire.**

*Apparatus.* A Reflecting Galvanometer: a Box of Coils: Metre Bridge: a Contact Key: Curve Paper: a constant Daniell.

*Experiment.* Short circuit the Daniell for five minutes. Connect the poles of the battery to the terminals at the ends $A$, $B$ of the metre wire (Fig. 11), introducing the contact key into the circuit as well as a resistance, if necessary, to keep the current small, so that the bridge wire may not be appreciably heated. Connect $A$ also through the box of coils to one terminal of the galvanometer. To the other terminal of the galvanometer a long wire is attached, with the free end of which contact can be made at any point of $AB$. Introduce a large resistance, some thousands of ohms, from the box of coils, so that when contact is made at $B$, the spot is deflected nearly to the end of the scale, and when made at $A$ there is at any rate a readable deflexion. A final adjustment may be made by altering the number of cells, or by moving the controlling magnet of the galvanometer. Since the resistance in the galvanometer branch is so large, (i) the current tapped from the main current on making contact is so small that the constant current sent by the battery through $AB$ is not thereby appreciably decreased. (ii) The introduction into the galvanometer branch of any length of $AB$ does not appreciably alter the resistance of the

branch, which remains therefore constant. Hence the current through the galvanometer or the deflexion of the spot is proportional to the difference of potential (P.D.)[32] between *A* and the given point of contact. Since the current through the metre wire remains constant, the P.D. between any two points is proportional to the resistance between them. The experiment consists in reading the deflexions of the spot when contact is made with the free end of the wire at different points along *AB*. Enter your results in a tabular form as follows:—

| Length of the bridge wire between *A* and the point of contact $l$ | Deflexions proportional to P.D. $d$ |
|---|---|
| ... | ... |
| ... | ... |
| ... | ... |

Plot a curve, taking the values of $l$ as abscissae, and those of $d$ as ordinates. If the wire be of uniform resistance throughout its whole length, the curve should be a straight line.

**The Post Office Box.** In the metre bridge (Fig. 11) the proportion between the two arms, *AD* and *DB*, is altered by moving the point *D*. In the Post Office form of Wheatstone's bridge the point *D* is fixed, and the proportion is altered by altering the resistances of the two arms themselves. Fig. 19 is

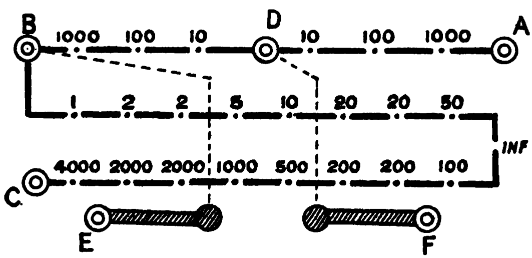


Fig. 19.

[32] The galvanometer placed in the high-resistance branch circuit acts here as a voltmeter.

a diagram of the Post Office box lettered according to Fig. 9. The ends of a resistance to be measured are joined to $A$ and $C$. One end of the battery is joined to $A$, the other end to the terminal of the contact key, $E$. When this key is down, connexion is made by a wire underneath with the point $B$. One end of the reflecting galvanometer is joined to $C$, the other end to the terminal of the contact key, $F$. When this key is down, connexion is made by a wire underneath with the point $D$. In practice the battery key must always be put down before the galvanometer key to prevent inductive action on the needle when the circuit is closed. The positions of the galvanometer and battery may be interchanged. The connexions should be tested by taking out the two 10-plugs in the arm $AB$ and then *momentarily* closing the circuits, first with no resistance out of the box, secondly when the INF plug is taken out. The deflexions should be in opposite directions. Suppose now when we make the proportional arms of equal resistance, i. e. by taking the 10-plug out of $BD$ and $DA$, we find the deflexion is in one direction when 5 ohms are out of the box and in the opposite direction when 6 ohms are out. The unknown resistance is between 5 and 6 ohms. Now make $BD$ ten times the resistance of $DA$ by taking out the 100-plug from $BD$ and the 10-plug from $DA$. To get no deflexion we shall have to take a resistance out of the box ten times as great as the unknown. Suppose we find that when we take out 57 the deflexion is one way, and when 58 is out the deflexion is in the opposite direction. The unknown resistance is between 5·7 and 5·8 ohms. Now take out the 1000-plug from $BD$ and the 10-plug from $DA$, making the proportion 100 : 1, and suppose the deflexion is in one direction when 573 ohms are out, and in the opposite direction when 574 ohms are out. The unknown resistance is thus between 5·73 and 5·74 ohms.

***29. To find the mean coefficient of increase in the resistance of a wire between two temperatures.**

*Apparatus.* A Reflecting Galvanometer : Post Office Bridge :

a Thermometer: a Beaker of Water on Tripod: Insulated Copper Wire of B.W.G. 25: a Battery Cell.

*Experiment.* Cut off about 3 or 4 metres of the wire, and doubling the length in the middle, wind it round a piece of glass tubing. Solder the ends to two thick copper wires, by which it may be attached to the terminals $A$, $C$, of the Post Office bridge, while completely immersed in a beaker of water placed on a tripod. Measure the resistance of the wire and note the temperature of the water. Now raise the water to about 80° and, keeping the temperature constant, again measure the resistance of the wire. The **mean coefficient of increase of resistance** of a given material, $a$, for a given rise of temperature is that increase of resistance which a wire of the material, having a resistance of 1 ohm at the lower temperature, undergoes when heated through the given range. Let $T$, $t$ be the higher and lower temperatures, and $R_T$, $R_t$, respectively the resistances of the wire at these temperatures, then

$$a = \frac{R_T - R_t}{R_t(T - t)}.$$

As a more advanced experiment, measure the resistance when the wire is heated about every 10°. The Bunsen's flame should be lowered and the water kept stirred so that the temperatures may be maintained constant while the measurements are being made. Draw a curve with the temperatures as abscissae and corresponding resistances as ordinates. Again, let the wire gradually cool and measure its resistances at gradually decreasing temperatures, and draw another similar curve on the same piece of paper. Finally, draw the average curve between the two, which should be approximately a straight line.

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## F. THE POTENTIOMETER AND ITS USE.

**The Potentiometer** is a uniform wire stretched along a graduated scale, provided with double terminals at its two ends. The base-board is of ¾-in. wood, 53 cm. long and 6 or 7 cm. wide. A sheet of drawing paper, 49 cm. long and 5 cm.

wide, is glued on to the board and then divided into centimetres by straight lines drawn parallel to its shorter sides. One end of an uncovered German silver or platinoid, or better still, a manganin wire, 2 metres long, is soldered to a strip of copper provided with a terminal, screwed into the board so that the edge of the copper strip coincides with an edge of the paper. The wire is stretched in a zigzag form round small screws, the horizontal lengths being 49 cm. and the distance between the screws being 2 cm. The free end of the wire is soldered to another copper strip provided with a terminal. Successive centimetres should be marked on the paper along the wire from 0 to 200.

**30. To compare electromotive forces by a null method.**

*Apparatus.* Potentiometer: a Reflecting Galvanometer: four constant Daniells: Bichromate: Leclanché: Grove.

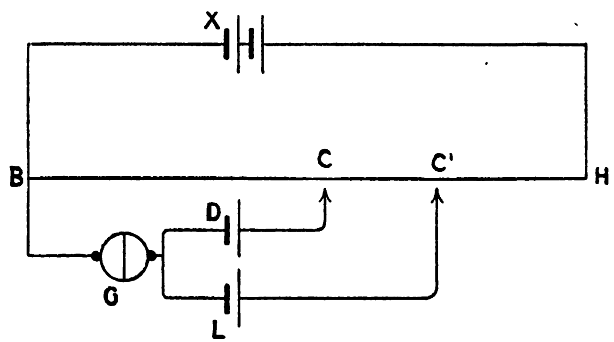


Fig. 20.

*Experiment.* Short circuit the Daniells for five minutes. To compare the E.M.F.'s of a Leclanché and a Daniell arrange the apparatus as in Fig. 20, where $X$ is a battery of 2 or 3 constant Daniell's cells joined to the ends of the potentiometer wire $BH$, through which it sends a constant current. To the end $B$ are also joined through the galvanometer $G$, the similar poles of a Daniell's cell, $D$, and of a Leclanché, $L$, these poles being similar to the pole of the battery $X$ which is joined to the same point $B$, so that all currents enter or leave at the

point $B$[33]. The other poles of $D$ and $L$ carry long wires, with the free ends of which contact may be made at will along the wire $BH$. An essential condition of the experiment is that the E.M.F. of the battery $X$ must be constant and greater than that of either of the cells to be compared. Make momentary contact successively near the two ends of the potentiometer wire with either of the free wires. If the connexions are right the spot of light should be deflected in opposite directions. If not, either $X$ is not a sufficiently high E.M.F. and another cell should be attached, or similar poles are not joined to $B$. Now there is a continuous fall of potential from $B$ to $H$ due to the main current sent by the battery $X$. Suppose this fall is $e_B^H$ and the length of the potentiometer wire is $l$. Since $X$ has a higher E.M.F. than the cell $D$, there must be some point, $C$, between $B$ and $H$ such that the fall of potential between $B$ and $C$ is equal to the E.M.F. of the cell on open circuit. On making contact at this point no current will pass through this branch circuit, and the galvanometer will not be affected. Find such a point $C$ and let $BC = a$. Let $E$ be the E.M.F. of the cell $D$, which in this case is equal to the difference of potential between $B$ and $C$ due to the battery $X$. Since the main current is supposed constant, the P.D. between any two points of its circuit is proportional to the resistance between these points;

$$\therefore \quad \frac{e_B^H}{E} = \frac{l}{a}.$$

Repeat the above for the cell $L$, and let $b$ be the distance from $A$, at which contact must be made with its free wire so that the galvanometer is unaffected. If $E_1$ be the E.M.F. of the cell $L$,

$$\frac{e_B^H}{E_1} = \frac{l}{b} \quad \text{or} \quad \frac{E_1}{E} = \frac{b}{a}.$$

As the main current may not be quite constant the above measures should be repeated.

It should be possible now to make contact simultaneously

[33] Two contact keys may with advantage be used, one put between the galvanometer and each of the two cells $D$ and $L$, so that these two branches may not be accidentally closed at the same time.

with the two free wires, so that the galvanometer is unaffected, in which case a more accurate value of the above ratio may be obtained. Taking the E.M.F. of the Daniell as 1·1 volt, find the voltage of the Leclanché. In a similar way find the voltage of the other cells, and by comparing pairs of cells test the accuracy of your observations as in Experiment 20.

Fill the cell $D$ a half or a third full only of liquids and observe that the zero point is the same as when it was full, showing that the E.M.F. of a cell does not depend upon its size.

Join two Daniells *in parallel* and show that their E.M.F. is the same as that of one cell only. Add a third cell to the battery $X$ and prove that the zero point for two Daniells *in series* is twice as far from $B$ as that for one cell, showing that the E.M.F. of two in series is twice that of one cell.

**31. To determine the strength of a current flowing through a wire of known resistance, and also the E.M.F. of a cell.**

*Apparatus.* Potentiometer Wire, whose resistance must be known: a Reflecting Galvanometer: a Tangent Galvanometer, whose reduction factor is known: three constant Daniell's Cells.

*Experiment.* Arrange the apparatus as in Experiment 30 (Fig. 20), omitting the cell $L$. Between $X$ and $B$ introduce the tangent galvanometer. Find the zero point $C$. The difference of potential between $B$ and $C$ is equal to the E.M.F., $e$, of the Daniell's cell $D$. Knowing the resistance of the wire $AB$, calculate that, $r$, of the portion of the wire between $B$ and $C$. The main current sent by the battery $X$ is $\frac{e}{r}$ by Ohm's Law. Taking $e$ as 1·1 volt, calculate the value of the current. Note the angle of deflexion on the tangent galvanometer $a$, and compare your result with $k \tan a$, where $k$ is its known reduction factor.

We have thus also an accurate method of determining the E.M.F. of a cell. If $C$ is the current in ampères given by the tangent galvanometer, and $r$ the resistance in ohms of $BC$, $E = Cr$ volts. Determine the E.M.F.'s of different cells in this way and compare your results with those obtained in other ways.

***32. To determine the back E.M.F. due to polarization.**

*Apparatus.* Potentiometer: a Reflecting Galvanometer: a Commutator without cross wires: an Electrolytic Cell, in which dip two platinum plates: two Bichromates.

*Experiment.* If water is decomposed in the electrolytic cell, the kathode will be polarized with hydrogen, the anode with oxygen. On breaking the decomposing current, and joining the kathode and anode through a galvanometer, a reverse current passing inside the cell from kathode to anode will take

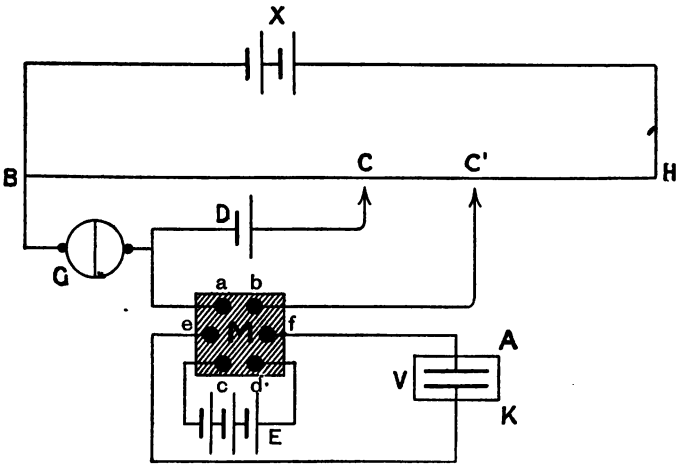


Fig. 21.

place, the hydrogen and oxygen again combining meanwhile to form water. The E.M.F. to which this reverse current is due is called the back E.M.F. of polarization. Join up the apparatus as in Fig. 21, where *BH* is the potentiometer through which a constant current is sent by the two Daniell's cells *X*, *M* the commutator without the cross wires, *V* the electrolytic cell containing platinum plates dipping in acidulated water, *E* the bichromates which are to decompose the water, *G* the reflecting galvanometer, *D* a constant Daniell, with the E.M.F. of which the back E.M.F. is to be compared. It is evident that

with this arrangement we have the means of either joining the electrolytic cell on to the circuit of $E$ to decompose the water, when the rocker dips in $c$, $d$, or on to the circuit of the potentiometer when the rocker dips in $a$, $b$. If $B$ is joined to the zinc plates of $X$ and of $D$ as in the figure, it must be also joined to the kathode, $K$, of the cell $V$, since the current due to the back E.M.F. of the polarized cell leaves it at the anode. Let the rocker wires dip in $c$, $d$, so that the water is decomposed for about two minutes. Find the zero point $C$ for the Daniell's cell $D$. Now tip the rocker over so as to put the bichromate cells $E$ out of circuit and to join the polarized cell on to the potentiometer. Find the zero point $C'$ for the back E.M.F., then

$$\frac{\text{back E.M.F.}}{\text{E.M.F. of Daniell}} = \frac{AC'}{AC}.$$

Repeat the above twice more, in each case previously switching the cell on to the bichromates, and take the average result.

Taking 1·1 as the voltage of the Daniell, it will be found that the voltage of the back E.M.F. is about 1·49. Hence one Daniell has too small an E.M.F. to decompose water.

Find as above the back E.M.F. due to the decomposition of ($a$) concentrated nitric acid and of ($b$) chromic acid.

***33. To determine the relation between the decrease in the E.M.F. of a cell due to polarization with the time it sends currents through different resistances.**

*Apparatus.* Potentiometer: a Reflecting Galvanometer: a Box of Coils : two constant Daniells : a Leclanché.

*Experiment.* Arrange the apparatus as in Fig. 20, omitting the Daniell's cell, $D$, and inserting a box of resistance coils between $L$ and $C'$. With no resistance out of the box determine the point of contact, $C'$, when the galvanometer is undeflected. Then $BC'$ is proportional to the E.M.F. of the cell on open circuit. Now introduce a large resistance, say 1,000 ohms from the box. It will be found that, keeping the free end of its wire in contact with the potentiometer wire, we shall have to move the point of contact gradually nearer $B$, in

order that the galvanometer may remain undeflected, showing that the E.M.F. of the cell gradually decreases, while it is sending a current. The experiment consists in moving the point of contact nearer *B*, so that the galvanometer remains undeflected, and noting the distances of the points of contact from *B* at equal intervals of time.

Plot a curve with the times as abscissae, and the corresponding distances as ordinates.

Allow the cell to remain on open circuit until it regains its original E.M.F., and repeat the above when resistances of 500, 250, 100, and 50 ohms are successively introduced, and finally with no resistance out of the box, and plot on the same piece of paper the corresponding curves.

The result will show that when a Leclanché is sending a large current its E.M.F. rapidly falls.

---

## G. Heating Effects of a Current.

**34. To prove that the heating effect of a current during the same time is proportional to the square of the current-strength.**

*Apparatus.* A Tangent Galvanometer: a Calorimeter as described below: a Thermometer reading to tenths of a degree: German Silver insulated Wire of about No. 29 B.W.G.: a Plug Key: a Watch: three Groves.

*Experiment.* The calorimeter should be of thin sheet copper, and of less than 100 c.c. capacity, packed round with sawdust inside a larger vessel. Its cover of cork or wood carries two terminals to which the wire is to be connected, and has two holes, one in which the thermometer is to be fixed, the other to hold a stirrer of thin copper wire coiled in a spiral. Wind in a coil about two metres of the German silver wire, and solder two thick pieces of copper wire to the ends by which it is to be connected to the terminals. Weigh the calorimeter, and multiply it by its specific heat to get its water value, $\mu$. Nearly fill the calorimeter with a known mass, $m$, of water, and place the cover on, so that the whole of the German silver wire is immersed in

the water. Omitting the calorimeter, join up the rest of the apparatus in series, and choose such a coil of the galvanometer that we get a deflexion of about 70°. Break the circuit, and introduce into it the calorimeter with the wire immersed in the water. Read the temperature. At a given moment close the circuit, and let the current run until the temperature has risen one or two degrees, keeping the water well stirred continually. Note the deflexion, $a$. At the end of the time break the circuit, read the temperature[34]. Note the loss of temperature during the same interval of time after the current is stopped, and add half the loss to the rise of temperature produced by the current. Let $t$ be the rise of temperature thus corrected for radiation. The heat developed by the current in the wire is $(m+\mu)\,t$ or $H$, neglecting the small amount of heat remaining in the wire. Alter the value of the current by introducing resistance or by removing a cell, and repeat the above. If $a'$ be the deflexion, and $t'$ the corrected rise of temperature during the same time as before, the heat developed is $(m+\mu)\,t'$ or $H'$, and we shall find that

$$H : H' :: \tan^2 a : \tan^2 a'.$$

***35. To measure in absolute electromagnetic units the difference of potential at the ends of a wire, and so to find the absolute value of the ohm.**

*Apparatus.* A Calorimeter, Thermometer, Stirrer, and Coil of German Silver Wire fitted together as in Experiment 34: an Electrolytic Cell, containing Copper Sulphate: a Rheostat or Box of Coils: a Watch: a Plug Key: three Groves.

*Experiment.* While a current $C$, measured in absolute electromagnetic units[35], flows through a wire between the ends of which there is a difference of potential $e$ in the same units, heat energy is developed between the two points at a rate of $Ce$ ergs per second. If the current flows for $n$ seconds, and we measure the heat, $H$, in calories by immersing the wire in water, then $$Cen = JH,$$

[34] If the water has been properly stirred the temperature will not continue to rise after the circuit is broken.

[35] See Appendix A, 2.

where $J$ is the mechanical equivalent of heat ($4 \cdot 2 \times 10^7$ ergs),

$$\text{or} \quad e = \frac{JH}{Cn}.$$

We have thus a means of measuring in absolute electromagnetic units the difference of potential between two points.

Connect up the electrolytic cell, key, rheostat and battery in series, and arrange the resistance and the number of cells in circuit, so that there is a good non-granular deposit of copper on the kathode. Take out the kathode, wash, dry, and weigh as in Experiment 2, and replace it. Nearly fill the calorimeter with a known mass, $m$, of water, having previously weighed it empty to determine its water-value, $\mu$. Introduce the calorimeter containing the thermometer wire and stirrer into the circuit, and read the temperature of the water. At a given moment make the circuit, and let the current run until the temperature has risen one or two degrees, suppose $n$ seconds, keeping the water well stirred. Read the thermometer. Break the circuit, and note the loss of temperature during the same interval, and add half the loss to the rise of temperature produced by the current. Let $t$ be the rise of temperature thus corrected for radiation. The heat developed in the wire is $(m+\mu)t$. Wash dry, and reweigh the kathode. Suppose $p$ the increase in mass due to the copper deposited. One electromagnetic unit of current deposits $\cdot 00326$ grs. of copper in one second, hence the current-strength, $C$, in absolute units is $\frac{p}{\cdot 00326\, n}$. Substituting in the above expression, we get

$$e = \frac{J(m+\mu)t \times \cdot 00326}{p}$$

as the value in absolute units of the difference of potential at the terminals of the wire in the calorimeter. Now

$$R = \frac{e}{C}.$$

Dividing the above value of $e$ by the current strength, we get the resistance of the wire in absolute units. Measuring the resistance in ohms by Wheatstone's bridge, we ought to find that one ohm is equal to $10^9$ absolute units of resistance.

## APPENDIX A.

**1. To prove that the least error is made in the measurement of a resistance by the metre bridge when the zero point is at the middle of the wire.**

If $l$ be the length of the bridge wire, and $a$ the distance of the point of contact from $A$ when there is no current through the galvanometer, and $R$ the resistance introduced from the box of coils, and $X$ the resistance to be measured,

$$X = R\frac{a}{l-a}. \qquad \text{(i)}$$

If an error, $y$, has been made in the position of the zero point, so that its correct distance from $A$ is $a+y$, and the true value of the unknown resistance is $X+x$,

$$X + x = R\frac{a+y}{(l-a)-y}. \qquad \text{(ii)}$$

Now $\dfrac{a+y}{(l-a)-y} = \dfrac{a+y}{(l-a)\left\{1-\dfrac{y}{l-a}\right\}} = \dfrac{(a+y)\left\{1+\dfrac{y}{l-a}\right\}}{l-a}$,

neglecting higher powers of $y$,

$$= \frac{a}{(l-a)}\left\{1 + \frac{ly}{a(l-a)}\right\}$$

$$\therefore \quad X+x = R\frac{a}{(l-a)}\left\{1+\frac{ly}{a(l-a)}\right\}$$

$$= X\left\{1+\frac{ly}{a(l-a)}\right\} \text{ from (i),}$$

$$\therefore \quad x = X\frac{ly}{a(l-a}.$$

The error $x$ is smallest when the denominator of this fraction is greatest, i.e. when $a = l - a$ or $a = \frac{l}{2}$, i.e. when the point of contact is at the mid-point of the metre-wire.

**2. Definition of the absolute electromagnetic or C.G.S. unit of current.**

The intensity of the magnetic field at any point, due to a very small elementary length of a wire conveying a current, varies inversely as the square of the distance of the point from the mid-point of the element, and acts perpendicularly to the plane containing the point and the elementary length of the wire. The intensity of the magnetic field, $F$, at the centre of a circular coil of wire conveying a current, varies as

(i) the current-strength, $C$;

(ii) the number of turns of wire, $n$, in the coil;

(iii) the sum of the elementary lengths, or the mean circumference, $2\pi r$, of the coil;

(iv) inversely as the square of the mean radius, or $\frac{1}{r^2}$.

$$\therefore \quad F \propto \frac{2\pi C n}{r},$$

$$\text{or} \quad F = K\frac{2\pi C n}{r},$$

where $K$ is some constant depending on the units employed to express the different quantities. The only undefined unit in the above expression is that of current-strength. For simplicity let us define our unit current to be that which, when flowing round a circular coil of a single turn of wire, of radius 1 cm., exerts upon a unit magnetic pole at the centre a force $2\pi$ dynes. With this definition $K$ becomes unity and the intensity of the field at the centre of a circular coil of $n$ turns, and of mean radius $r$ cm., through which a current, of strength $C$ units, circulates is given by

$$F = \frac{2\pi C n}{r} \text{ dynes on unit pole.}$$

The unit of current as above defined is the absolute electromagnetic or C.G.S. unit. The practical unit, the *ampère*, is $\frac{1}{10}$th of this absolute unit. The *volt* is $10^8$ times, the *ohm* is $10^9$ times the C.G.S. unit of difference of potential and of resistance respectively.

If a short compass needle is suspended at the centre of the coil, and the plane of the coil lies in the magnetic meridian, the field in which the needle swings is perpendicular to the magnetic meridian, and may be considered uniform. Hence if the needle is deflected an angle $a$ from the meridian by the current,

$$F = H \tan a.$$

Equating the two values of $F$ we get

$$C = \frac{rH}{2\pi n} \tan a.$$

Hence at a given place where $H$ is constant, the current-strength varies as the tangent of the angle of deflexion produced. $\frac{r}{2\pi n}$ is called the *galvanometer constant*, depending only on the construction of the instrument, and $\frac{rH}{2\pi n}$ the *reduction factor* of the galvanometer, depending, in addition, on the horizontal intensity of the earth's magnetic force at the place.

*Practical Units.*

| | | | | | |
|---|---|---|---|---|---|
| 1 ampère | equals | $\frac{1}{10}$th of the C.G.S. unit of current. | | | |
| 1 ohm | ,, | $10^9$ | ,, | ,, | ,, |
| 1 volt | ,, | $10^8$ | ,, | ,, | ,, |

**3. A new form of Ammeter and Voltmeter.**

The ammeter shown in Fig. 22 is a new instrument invented and patented by Mr. Baker, of the Municipal Technical School at Birmingham. It is of the hydrometer type, and consists of a vertical brass tube about 35 cm. long, closed at the bottom, and terminating at the top in a screw collar. The collar carries a glass tube closed at the top, to the inside of which the scale is attached. Upon the lower part of the brass tube and upon about 10 cm. of its length a suitable quantity of insulated copper wire is closely coiled, and the ends of the coil are fastened to the terminals, as shown in the figure. The

moving part of the instrument consists of a glass float, in shape like a pippette, with a cylindrical bulb, but very light. The lower extension of the float carries within it one or more wires of annealed charcoal iron. The upper extension serves as an index, and moves over the scale in a vertical direction. The brass tube referred to above is charged with petroleum (Royal Daylight, sp. gr. ·8), and the float, properly ballasted, is suspended in the liquid. To prevent the float touching the wall of the containing tube, and to confine its movement to the axis of the same, a pair of guide-plates is provided, one immediately above the top of the coils, and the other near the top of the tube, just below the surface of the petroleum. Each plate is perforated at its centre, and the boundary of the perforation is reduced to a knife-edge.

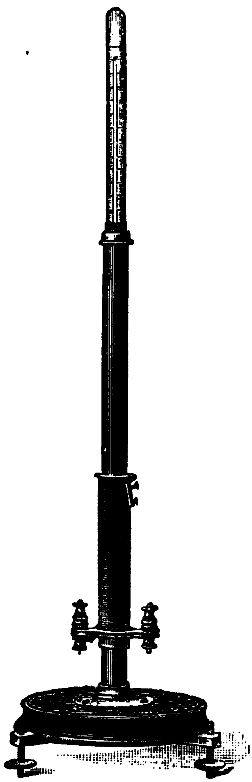

Fig. 22.

By means of a brass flange foot 5·5 cm. in diameter, the instrument may be screwed directly to the working bench, or mounted on a stand for portable use.

The construction of the voltmeter is precisely similar, substituting a winding of high resistance instead of the shorter and thicker wire used for the ammeter. The ammeter may be used instead of the tangent galvanometer, and the voltmeter instead of the reflecting galvanometer, in the high-resistance circuit in the above Experiments. It is evident that the reduction factor of the tangent galvanometer may be determined at once by connecting it in series with the ammeter.

# APPENDIX B.

## 1. Resistances in legal ohms per metre at 15° C. of pure Copper and German Silver wires according to the Birmingham Wire Gauge.

| B.W.G. No. | Nearest S.W.G. No. | Diameter in m.m. | Resistances | |
|---|---|---|---|---|
| | | | Copper | German Silver |
| 12 | 12 | 2·77 | ·00286 | ·03718 |
| 14 | 14 | 2·11 | ·00492 | ·06396 |
| 16 | 16 | 1·65 | ·00804 | ·10452 |
| 18 | 18 | 1·24 | ·0141 | ·1833 |
| 20 | 20 | ·889 | ·0277 | ·3601 |
| 22 | 22 | ·711 | ·0433 | ·5629 |
| 24 | 24 | ·559 | ·0701 | ·9113 |
| 26 | 26 | ·457 | ·105 | 1·365 |
| 28 | 28 | ·356 | ·173 | 2·249 |
| 30 | 30 | ·305 | ·235 | 3·055 |
| 32 | 34 | ·229 | ·419 | 5·447 |
| 34 | 36 | ·178 | ·693 | 9·009 |
| 36 | 42 | ·102 | 2·13 | 27·69 |

## 2. Electromotive Forces of Galvanic Cells in Volts.

| | | |
|---|---|---|
| Volta | Zinc<br>Water<br>Copper | about 1 |
| Leclanché | Amalgamated Zinc<br>Solution of Sal Ammoniac<br>Manganese Dioxide and Carbon | 1·46 |
| Bichromate | Amalgamated Zinc<br>12 Potassium Bichromate, 25 Sulphuric Acid, 100 Water<br>Carbon | 2·01 |
| Daniell | Amalgamated Zinc<br>1 Sulphuric Acid, 10 of Water<br>Saturated Solution of Copper Sulphate | 1·12 |
| Grove or Bunsen | Amalgamated Zinc<br>1 Sulphuric Acid, 12 Water<br>Nitric Acid<br>Platinum or Carbon | 1·88 |

### 3. Specific Resistances of Metals and Alloys in ohms per c.c. and mean Temperature Coefficients.

| | *Specific Resistance.* | *Temperature Coeff.* |
|---|---|---|
| Silver annealed | $149 \times 10^{-8}$ | ·00384 |
| „ hard drawn | $162 \times 10^{-8}$ | |
| Copper annealed | $158 \times 10^{-8}$ | ·00394 |
| „ hard drawn | $162 \times 10^{-8}$ | |
| Platinum | $898 \times 10^{-8}$ | ·00247 |
| Mercury | $941 \times 10^{-7}$ | ·000887 |
| German Silver | $207 \times 10^{-7}$ | ·0004 |
| Brass | $5·8 \times 10^{-7}$ | ·00125 |
| Manganin | $420 \times 10^{-7}$ | ... |

### 4. Specific Resistances in ohms per c.c. and Densities of Solutions of Copper and Zinc Sulphates.

| One part of the Crystal in the following parts of water | At 10° C. | | | |
|---|---|---|---|---|
| | Copper Sulphate | | Zinc Sulphate | |
| | Density | Sp. Resist. | Density | Sp. Resist. |
| 40 | 1·0167 | 164·4 | 1·0152 | 182·9 |
| 20 | 1·0318 | 98·7 | 1·0276 | 111·1 |
| 10 | 1·0622 | 59 | 1·0586 | 63·8 |
| 5 | 1·1174 | 38 | 1·1004 | 42·1 |
| 2·6 | 1·2054 (satd.) | 29·3 | ... | ... |
| ·752 | ... | ... | 1·4172 (satd.) | 33·7 |

### 5. Electro-chemical Equivalents, Atomic Weights, and Valencies of Elements.

| | *Atomic Weights.* | *Valencies.* | *Electro-chemical Equivalents.* Mass deposited in 1 sec. by 1 ampère. |
|---|---|---|---|
| H | 1 | 1 | ·00001038 |
| O | 16 | 2 | ·0000828 |
| Cu (ic) | 63 | 2 | ·000326 |
| Ag | 108 | 1 | ·001118 |
| Zn | 65 | 2 | ·0003367 |

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